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PROJECT NO. 229-198

PRECISION FREQUENCY CONTROL TECHNIQUES
(500 Mc and Higher)

D. W. FRASER
PROJECT DIRECTOR

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DEPARTMENT OF THE ARMY PROJECT: 3-99-11-022
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By

VERNON CRAWFORD AND DONALD W. FRASER

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FEBRUARY 1, 1953 TO MAY 1, 1953

PLACED BY THE U. S. ARMY
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I. PURPOSE

The purpose of this project is threefold: (a) to continue work on the stabilization of oscillators between 500 and 3000 Mc, using cavity resonators, (b) to investigate any new phenomena of resonance that occurs in the range of 500 to 3000 Mc and which may show promise of some success, and (c) to undertake any other investigations which may arise during the course of the work outlined in (a) and (b) above, or which may be mutually agreed upon between the Contractor and the Contracting Office or his representative.

By agreement with the sponsor, investigations of resonances below 500 Mc may be prosecuted as preliminary steps in determining the feasibility of frequency control by the phenomena under study. In addition, cavity resonators previously under construction and designed to provide control of frequencies below 500 Mc may be completed and tested as aids in perfecting measurement techniques which will be later applied to the 500 Mc and above range of frequencies.

II. ABSTRACT

A conference with representatives of the Signal Corps early this quarter resulted in a decision to concentrate upon two phases of experimental work during the year. These two phases are respectively: (1) continuation of research on coaxial cavities as mediums for oscillator control, utilizing the information gained under a previous project, and (2) initiation of studies of the absorption and transfer characteristics of piezoelectric quartz crystals when excited at very high orders of mechanical overtones.

Three new cavities have been designed during the period of this report. The one to which the most attention has been devoted is constructed, in the main, of Stupalith, a ceramic material having a claimed coefficient of expansion of zero parts per million per degree centigrade. The overall value of this material in cavity construction cannot be determined with this cavity, since neither Stupalith rod or tubing was available as material for the center conductor; the major value of the cavity has been to indoctrinate personnel into the methods of machining and plating this ceramic material.

Another cavity was constructed completely of brass. It was intended to serve as a convenient test vehicle for oscillators and for the Cavity Q-Meter described below. The known large coefficient of expansion of brass permits an evaluation of the characteristics of the equipment coupled to the cavity.

The third and final cavity contains a silver-plated brass outer conductor, a silver-plated Vycor inner conductor, plus a compensation section designed to produce a first order correction for temperature effects on frequency. Tests of this cavity are to be prosecuted in the near future.

A Cavity Q-Meter has been constructed to permit studies of the coaxial cavities as passive resonators rather than as active parts of an oscillating system. This device features a frequency-swept oscillator, a variable-frequency oscillator, and a band-pass amplifier.

Their combined use permits a simultaneous CRT presentation of the cavity response curve and of pairs of markers with which to measure the band width of the response curve. This equipment shows considerable promise in facilitating future measurements of cavity resonators.

Crystals have been tested in three separate ways for high order harmonic response. 1) Unmounted crystals have been placed in a radio frequency electric field and have given responses up to the frequency limit of the presently available equipment. 2) Mounted crystals with loops across their terminals have been placed in the vicinity of the oscillator coils and have shown strong absorptions up to the forty first overtone of the crystal fundamental. 3) A transfer circuit, consisting of a crystal and loop, has been used to couple an oscillator to a detector. This mechanism has proved successful to the upper frequency limit of currently available equipment.

Crystal control of frequency has been achieved utilizing the third of the above mentioned effects.

III. CONFERENCES

Representatives of the Signal Corps and technical personnel involved with this project at the Georgia Institute of Technology met in conference at the Squier Signal Laboratory, Fort Monmouth, New Jersey on February 20, 1953. The purpose of this meeting was to discuss various factors related to the project, to insure mutual understanding of the problems involved in proposed investigations, and to adapt the program of research to those topics considered to be of paramount interest to the Signal Corps.

Five suggested topics for research were considered. These topics consisted of the following: (a) Cavity resonances, (b) Magnetic resonances, (c) Quadrupole resonances, (d) High-order Harmonic selection, and (e) High-order overtone excitation in quartz crystals. These topics were each examined in detail, with a result that it was mutually agreed that major emphasis of the research program should be directed toward subject (a), Cavity resonators, with secondary emphasis on subject (e) Crystal overtone excitation. The other topics were not to be pursued, with the exception that should literature study disclose any new and unusual possibilities in the field of quadrupole resonances that further attention might be directed toward that type of phenomenon.

IV. COAXIAL CAVITY RESONATORS

Introduction

During the period of this report the information gained under a previous Contract ⁽¹⁾ has been utilized as a guide toward improvement of the characteristics of cavity resonators. Experiments conducted under the contract referred to have indicated that materials with extremely low coefficients of expansion may be profitably utilized as constituent parts in resonator assembly. The experiments have further indicated that a method of temperature correction may be applied in order to considerably reduce, in theory, the frequency variation below that existing in the absence of such compensation.

Search for a material having an extremely low coefficient of expansion has elicited information on the ceramic Stupalith ⁽²⁾. This material was reported upon in the previous contract noted above but was not utilized in a resonator. Sample plates and tubing have been recently obtained and have been incorporated into a 300 Mc/sec coaxial cavity resonator. Unfortunately no tubing of this material was available for the center conductor; a substitute consisted of a silver-plated Vycor tube. The construction of this resonator has served primarily to indoctrinate personnel in the procedures required to properly machine, silver-plate, and assemble the ceramic components. At present an order has been placed with the manufacturers of the ceramic to furnish prefabricated sections of Stupalith; receipt of these components is expected momentarily. It is believed that serious difficulties in machining will be obviated by prefabrication and that resonator construction will be simplified.

One temperature compensated resonator has been constructed. Details are found in the following section. In addition, a non-compensated, open-ended cavity with interchangeable center conductors has been constructed. This latter cavity is intended, primarily, to serve as a convenient test vehicle for Q and frequency measuring equipment. It has, however, a secondary function of serving as a tuned circuit for various oscillators being constructed, a tuned circuit of only moderate Q but

one whose resonant frequency may be quickly shifted by insertion of a new center conductor of desired length.

Ceramic Base Resonator.

The temperature coefficient of one form of Stupalith ⁽²⁾ is stated to be approximately zero parts per million per degree centigrade. Its possible application here has been long considered but the feasibility of utilization of this type of material depended upon the answers to two obvious questions: (1) could it be machined with sufficient precision to insure a uniform surface around holes, shoulders, etc., and (2) could a silver coating be applied which would not only produce a fine, highly conductive surface but which in addition would remain completely stable during moderately wide variations of temperature.

Tests and experimental procedures have given a qualified positive answer to both questions. Diamond or silicon carbide grinding and cutting tools will adequately machine the ceramic plates and tubes, but great care must be exercised to prevent chipped edges on the machined surfaces. Silver-plating may be completed in two steps. In the first step Du Pont number 4760 silver paste ⁽³⁾ is applied with a small spray gun and, after drying, is fired at a temperature of 1200° F. The resulting film is polished and then electroplated to a thickness of from 1 to 2 thousandths of an inch. The final coating appears to have the normal conductive properties expected. However, it has been discovered that gases entrapped within the porous centers of the ceramic materials limit the temperature range of usefulness. Temperatures not higher than 300° F and possibly as low as 250° F produced an internal gas pressure sufficient to cause bubbles in the silvered surface. It is evident therefore that a cavity constructed of such ceramic parts must be provided with adequate cooling when in the presence of heat radiating components.

The resonator constructed from these components is sketched in cross-section in Fig. 4-1. Extensive tests are being prosecuted to ascertain the mechanical stability of the various bonding surfaces during controlled temperature variations, and to also determine the effect of these same bonding surfaces upon the electrical properties of the resonator.

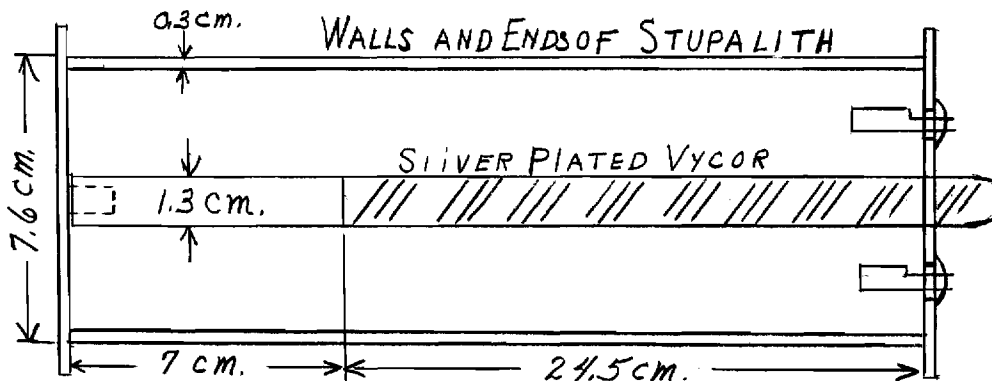
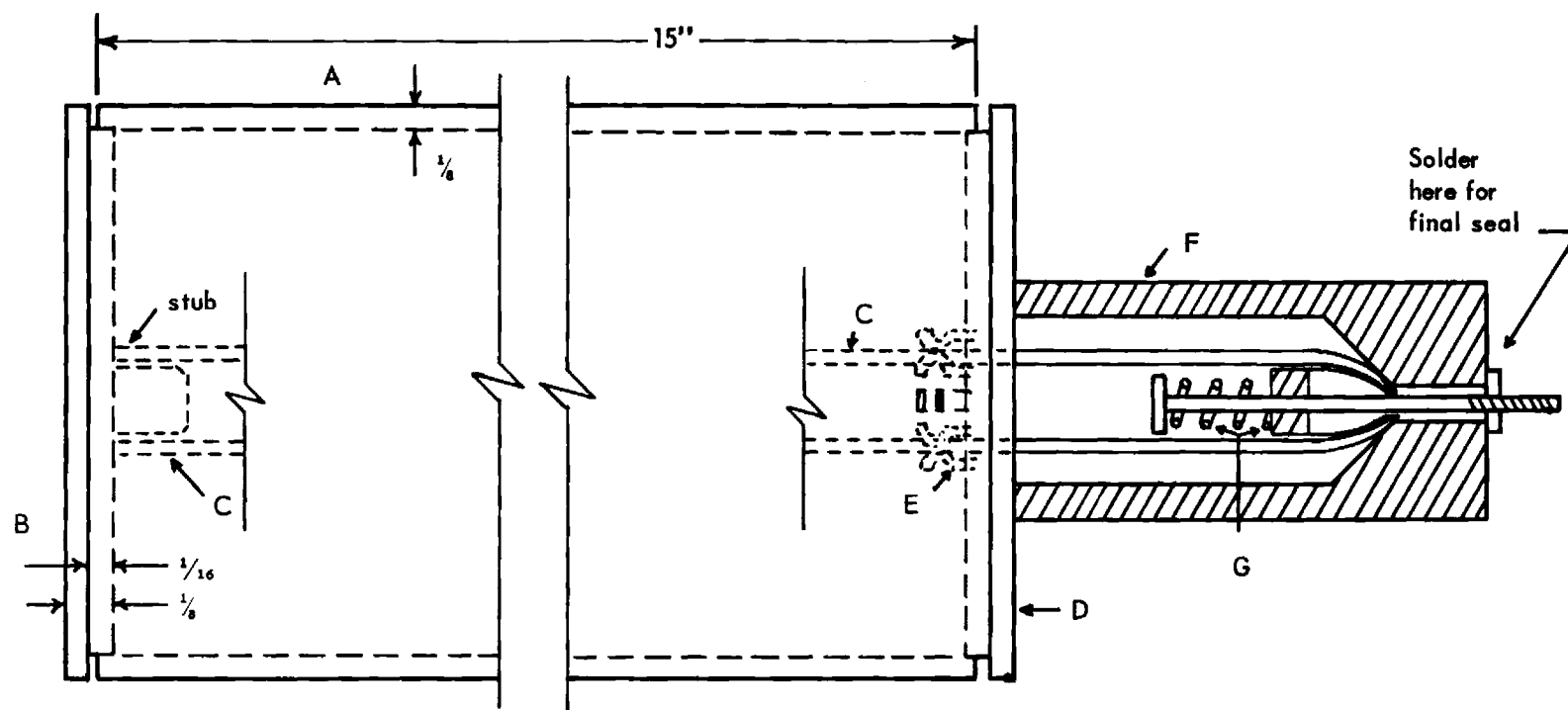


Figure 4-1. Coaxial Cavity Utilizing Ceramic Walls.

Compensated Cavity.

Cavities utilizing a form of temperature compensation were constructed under the previous contract. ⁽¹⁾ These contained the equivalent of two coaxial cavities, one very much smaller than the other and with a low characteristic impedance. Although this arrangement has attractive theoretical frequency stability as a function of temperature, it is difficult to construct because the tolerances required for realization of the theoretical properties are quite severe. A somewhat simpler method has been utilized in a cavity which has been recently constructed. Details are shown in Fig. 4-2.

In this figure the active electrical length of the center conductor is L_0 . The outer conductor and the end cap are composed of brass. Brass has a temperature coefficient of expansion of approximately 20 parts per million per degree centigrade. The inner conductor is composed of Vycor, silver-plated over the active area. Vycor has a temperature coefficient of expansion of about 1/20th that of brass. Inasmuch as the Vycor extends into the brass end-cap a length x , it is only necessary that x be 1/20 of L to effect a first order compensation for dimensional changes



Assembled view, consisting of following units:

- A. Hollow Tubing 15" long, $1\frac{3}{4}$ " O. D., $1\frac{5}{8}$ " I. D. (Brass)
- B. End Plate, $\frac{1}{4}$ " Brass with stub support for Vycor tubing
- C. Vycor tubing, silver plated 24.5 cms from end plate D
- D. End plate E. Bergllium copper, silver plated, contact fingers
- F. Pressure sealing cap (in cross section)
- G. Spring and flexible pressure transfer section

Figure 4.2. Temperature Compensated Brass Resonator.

due to temperature variations. A mechanical difficulty is associated with this resonator in the nature of a sliding short circuit between the inner conductor and end wall of the cavity. The total surface in contact between the inner conductor and the flexible silvered fingers is quite small (slots between the fingers comprise nearly one-half the circumference) so a reduction of cavity Q must be expected. Tests now in progress are expected to produce data by which an objective comparison of the relative advantages and disadvantages of this type of compensation and of the previous variety may be made.

Experimental Determination of Dynamic Characteristics.

The experimental cavities constructed under the previous contract⁽¹⁾ were invariably tested through the expedient of utilizing the cavity as the frequency sensitive element in the feedback loop of an oscillator. This procedure had considerable merit in predicting the overall characteristics of the oscillator. However, it failed to completely differentiate between the effects of the cavity and of other parts of the circuit upon frequency deviations when these deviations are functions of temperature. It became evident that the determination of the dynamic characteristics of the cavity alone would be facilitated by the adoption of other techniques. The most promising device permitting rapid but accurate measurements of cavity characteristics is a dynamic Q meter with which the cavity serves as a passive, rather than active, portion of the equipment. The Q meter acts as a radio frequency generator of controlled frequency, amplitude, and impedance, by its use the cavity may be theoretically disengaged completely from other circuitry. The cavity may, for example, be isolated in a temperature-controlled testing oven from which it is coupled to the Q meter with lines which are made non frequency-selective by the utilization of proper matching techniques. The effects of temperature upon frequency deviation, cavity Q , etc. may be determined while the ambient temperature of all parts of the driving generator is held constant.

A cavity Q meter designed to achieve the objectives outlined above has been in the process of construction and is at the date of writing undergoing initial tests. The theory and practice of such a Q meter, and the analysis required to determine cavity characteristics, are discussed in section VI of this report.

V. THE HIGH-ORDER OVERTONE RESPONSE OF QUARTZ CRYSTALS

During the course of the work on nuclear quadrupole resonances it was found convenient to locate the frequency of the quadrupole spectrometer, and test its sensitivity, by using a quartz crystal operating on an overtone frequency, as a reference absorber. The technique, as has previously been described ⁽¹⁾, was to connect a loop of wire across the terminals of a mounted AT-cut quartz crystal, and to place this loop in the vicinity of the tank-coil of the frequency-modulated detector. The absorption of the crystal was displayed on an oscilloscope in the same manner as was used to display the quadrupole absorption.

A comparison of the two responses proved very interesting. They were similar in their general appearance, but differed in some important details. First the selectivity of the quadrupole resonator was higher than that of the crystal; second the quadrupole resonance was temperature sensitive to a much higher degree than the crystal resonance; and third, (this was very discouraging at the time) the magnitude of the response from the quadrupole resonance was considerably less, in many instances, than the response from the crystal. The last two differences, in the opinion of the investigators, considerably outweighed the first insofar as comparing the two phenomena for their applicability in the field of frequency control is concerned, and strongly suggested that the quadrupole research be abandoned in favor of an investigation of the possibility of using quartz crystals, operating at higher overtones than had previously been utilized, as frequency controlling elements.

Other observations were made which also indicated that piezo-electric crystals might be made to yield sizeable responses at high frequencies. For example, in the course of the investigation of the nuclear quadrupole resonance of sodium chlorate, NaClO_3 , responses were observed which at first were believed to be due to the quadrupole moment of the chlorine, but which further tests revealed to be a manifestation of the absorption of the piezo-electric NaClO_3 crystals. These responses disappeared, or at least shifted frequency outside the range of the detector, when the sample was pulverized to a fine powder. Quartz crystal blanks,

and pieces of broken blanks, when placed in the vicinity of the oscillator coil also showed responses due to absorption. It was felt that a crystal excited in this manner might be capable of vibrations in very high overtones of the fundamental frequency because much of the loading inherent in a conventionally mounted crystal is absent.

During the past quarter a certain amount of exploratory work on various aspects of high overtone excitation of quartz crystals has been carried out. The point of view adopted has been that at this beginning phase of the investigation it would be unwise to concentrate on any one aspect of the problem to the exclusion of others. Therefore, although not much concrete data has been collected, several preliminary investigations have been carried out with the result that some insight has been gained as to the lines of attack likely to prove most fruitful in the future.

In the first attempt to improve the crystal response a frequency-modulated oscillator, which had been used in the quadrupole research, and which had a frequency range centering about 25 Mc was modified slightly. The modification consisted of connecting a capacitor across the tank coil of the oscillator. This capacitor consisted of two brass plates about an inch and a half square and separated by approximately two inches (variable). The capacitance amounts to less than a third of a micro-micro farad and so does not lower the frequency of the oscillator appreciably. A 5 Mc. crystal blank was held between the plates of the capacitor and the response at 25 Mc. was searched for. Two other plates, at right angles to the first pair, served as detectors of the crystal response. One of these plates was grounded and the signal from the other was fed through an amplifier and thence to an oscilloscope. It was reasoned that the crystal should be excited more strongly in such an environment than in the vicinity of the coil itself because in the latter case the field is principally magnetic. The desired response was observed and was gratifyingly strong. However it was difficult to obtain reproducible magnitudes of the response. The signal strength appeared to be critically dependent on the orientation of the crystal and the spacing of the exciting plates. Another similar device with fixed spacing, and in which the crystal orientation could be more easily controlled, was constructed but it yielded discouraging results

for reasons which are not as yet understood. This general method of attack was abandoned for the time being but will be pursued again at higher frequencies and with a more stable system.

Another approach to the problem made use of a conventionally mounted crystal with a loop connected across its terminals. Fig. 5.1 illustrates the general method. Coils A and C were essentially decoupled by proper positioning so that at all frequencies except those corresponding to crystal resonances no observable signal was presented on the oscilloscope. At a crystal resonance frequency, however, a transfer took place via the circuit B which was coupled inductively to both A and B, but which at all other frequencies had a sufficiently high impedance to prevent transfer action.

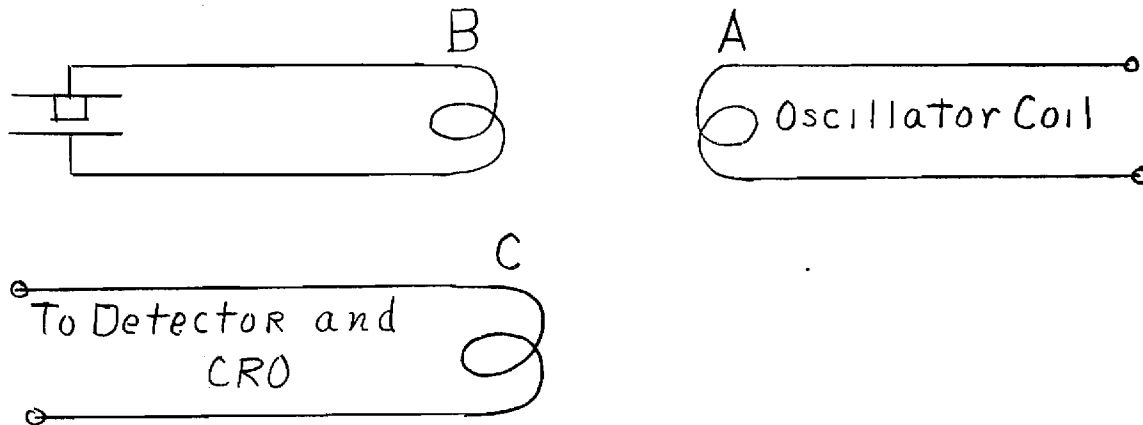


Figure 5.1. Transfer System

Several crystals were tested by this method. All of them gave strong responses at frequencies corresponding to odd harmonics of their fundamentals within the frequency range of the equipment which extended only to about 50 Mc. For example a 5 Mc crystal produced a signal on the oscilloscope at 45 Mc which corresponded to a 3 volt signal at the coil C. There is every reason to believe that this particular test can be duplicated at much higher frequencies.

If the phenomenon just discussed persists at frequencies in the range of a few hundred megacycles, it will be desirable to have a circuit available with which frequency control by this method can be achieved.

A reasonably successful start in this direction has been made. The circuit of Fig. 5.2 has been constructed and subjected to some simple tests.

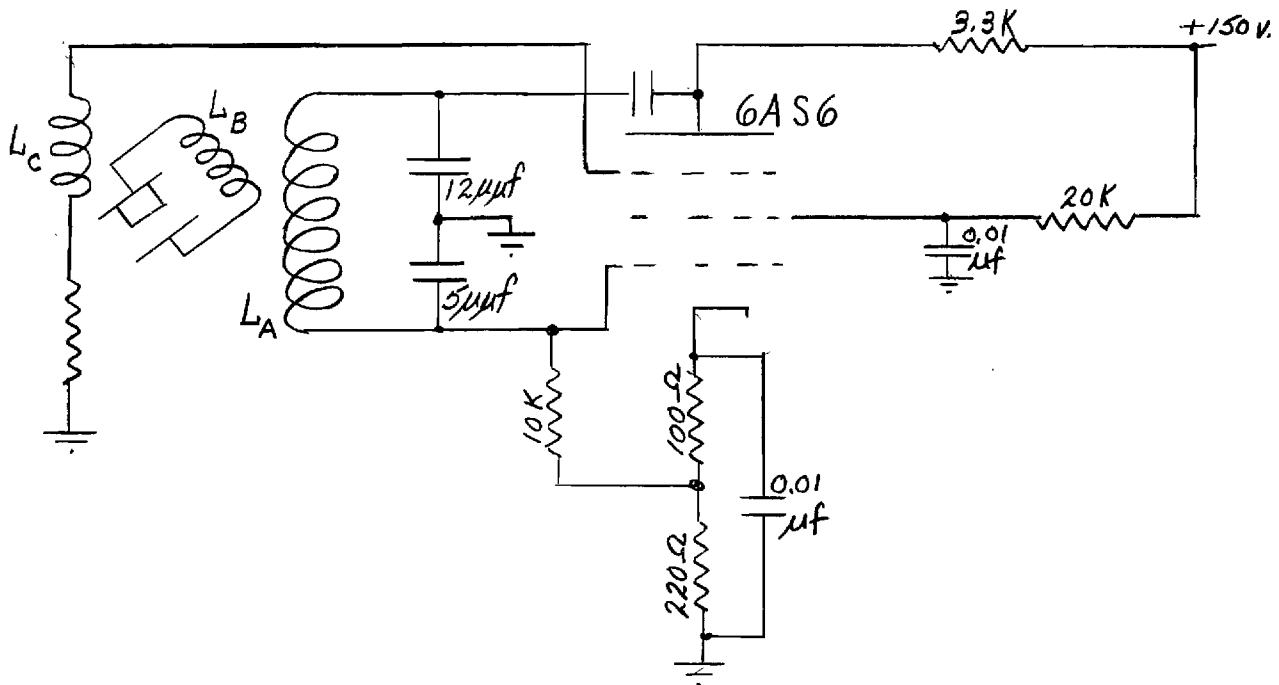


Figure 5.2. An Oscillator Frequency Controlled by the Transfer Action of a Crystal

The principle of operation of the circuit of Fig. 5.2 is relatively straightforward. It is essentially a Colpitts oscillator in which the d.c. bias is adjusted so that the point of operation is at the point of maximum slope on the transconductance curve of the suppressor grid. At this bias oscillations are inhibited except at those frequencies corresponding to an odd crystal harmonic. At one of the latter frequencies the transfer of energy from L_a to L_c via L_b induces an r.f. voltage on the suppressor of the correct phase to sustain oscillations.

In the actual test the crystal had a fundamental frequency of 5 Mc. When the oscillator was tuned to 35 Mc., corresponding to the seventh harmonic of the crystal, a certain degree of control was achieved. With the crystal removed the device either did not oscillate at all, or did so with a very small amplitude. With the crystal inserted the oscillations were much stronger and the frequency was found to be crystal controlled to the extent that it did not vary when small changes occurred in the tuning capacitor.

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The principle of this device is not new, but the experiment was encouraging in that it suggested that frequency control by the transfer action is feasible.

A frequency-modulated oscillator which was capable of oscillating at slightly above 200 Mc. was constructed. With it the forty-first harmonic of a five Mc. crystal gave a strong response.

VI. CAVITY Q METER TECHNIQUE

Introduction.

A well known technique for determining the response of a tuned circuit is the so called "swept-frequency" process. In this technique a frequency modulated signal is impressed upon the tuned circuit and the magnitude of signal transmitted by the circuit is observed or recorded by appropriate equipment. If all portions of the equipment exterior to the circuit under test are non-frequency selective it is possible to obtain a measured output which is a true frequency response curve of the tuned circuit. The essential requirements of such a system include the following: (1) it must be capable of producing a frequency-modulated signal which shall have negligible amplitude modulation and which is capable of sweeping a frequency band considerably greater than that represented by the frequency response band of any circuit under test, (2) it must be conveniently tunable and should desirably exhibit a relatively high order of frequency stability, and (3) it must include an output circuit which exhibits an amplitude response which is linear with respect to amplitude of the signal transmitted through the cavity. The last requirement may be modified to permit some non-linearity by preparation and use of calibration curves of output-vs-input amplitudes.

Although the basic equipment discussed is capable of producing an output which is proportional to the response curve of the tuned circuit, it is incapable of providing further data without additional components. If, as usual, the observing and/or recording device is a cathode ray oscilloscope, a visual picture of the response curve is presented but such factors as center frequency, f_a , and band-width, $f_2 - f_1$, cannot be determined. It is the purpose of this section to describe an apparatus which permits rapid determination of f_a , the center frequency, of $f_2 - f_1$ the band-width (and hence Q by the relationship $Q = f_a / (f_2 - f_1)$), and of variations in these due to various controlled parameters. Inasmuch as the tuned circuits concerned in the project consist of coaxial cavities, the name cavity Q-meter is appropriate.

Components of the Cavity Q-Meter.

The basic plan as outlined by Young ⁽⁴⁾ was adopted for the initial layout of a Q-meter. Numerous changes were later incorporated to permit a maximum of utilization and of flexibility.

The components for the Q-meter are shown in Fig. 6-1. R-F power in the UHF region is generated by a frequency-modulated oscillator and is transmitted through the test cavity to a detector. The detected, amplified signal drives the vertical deflection plates of a cathode ray

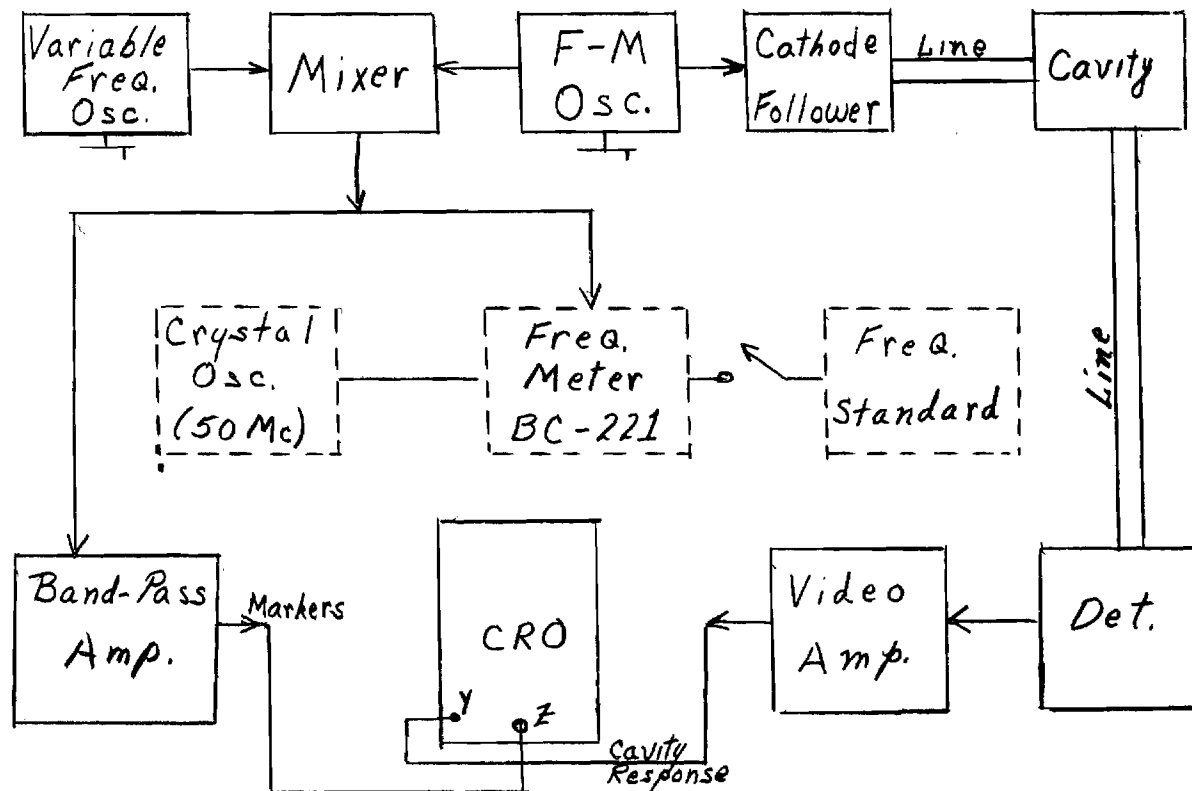


Figure 6-1. Block Diagram of Cavity Q-Meter.

oscilloscope. The output of the f-m oscillator is also fed to a mixer where heterodyne action occurs with a signal from the variable frequency oscillator. The difference frequencies in the mixer output are now subjected to selective, narrow-band filtering in the band-pass amplifier.

By a proper setting of each oscillator it is possible to produce difference frequencies at two different points when the f-m oscillator is either above or below the frequency of the variable oscillator. These difference frequencies will be transmitted through the band-pass amplifier. The presence of high Q tuned circuits in this amplifier assures that the two transmissions consist of pulses which have large amplitude but are relatively narrow. These pulses, when amplified, are used to intensity-modulate the cathode-ray tube and thus produce spots, or markers, on the response curve of the cavity. When these markers are adjusted so as to be equidistant from the baseline, the variable oscillator will be generating a frequency which corresponds to the resonant frequency of the cavity. If the band-pass amplifier is adjusted so that the spots occur at the cavity half-power points their frequency separation is equal to the band-width of the cavity.

Frequency measurements may be obtained in several ways but a convenient method, and one utilized by the writers, is illustrated in the block diagram. The output of a crystal controlled high frequency oscillator is superimposed upon the variable oscillator. A number of difference frequencies will be found in the output of the mixer as the fundamental frequency of the variable oscillator beats with various harmonics of the crystal controlled oscillator. By proper choice of the latter's fundamental frequency, (usually 50-60 Mc.) a difference frequency of as low as a few kilocycles can be produced. In any case, it is not difficult to obtain a difference frequency of not greater than a few megacycles. In this case a low-frequency stable frequency meter permits measurements to excellent degrees of accuracy. Greater accuracy, if required, can be obtained by checking the crystal-controlled oscillator against a fundamental frequency standard by the method indicated in the block diagram. An equivalent check of accuracy can be applied to the frequency meter.

A schematic of the equipment is shown in Fig. 6-2. The number of stages required at some points of the circuit is not necessarily fixed, the number shown represents a probable minimum. For example, the amplitude response of certain cavities may be so low as to require the addition of more stages of amplification in the video amplifier. The band-pass amplifier, also, may require more stages of amplification than are

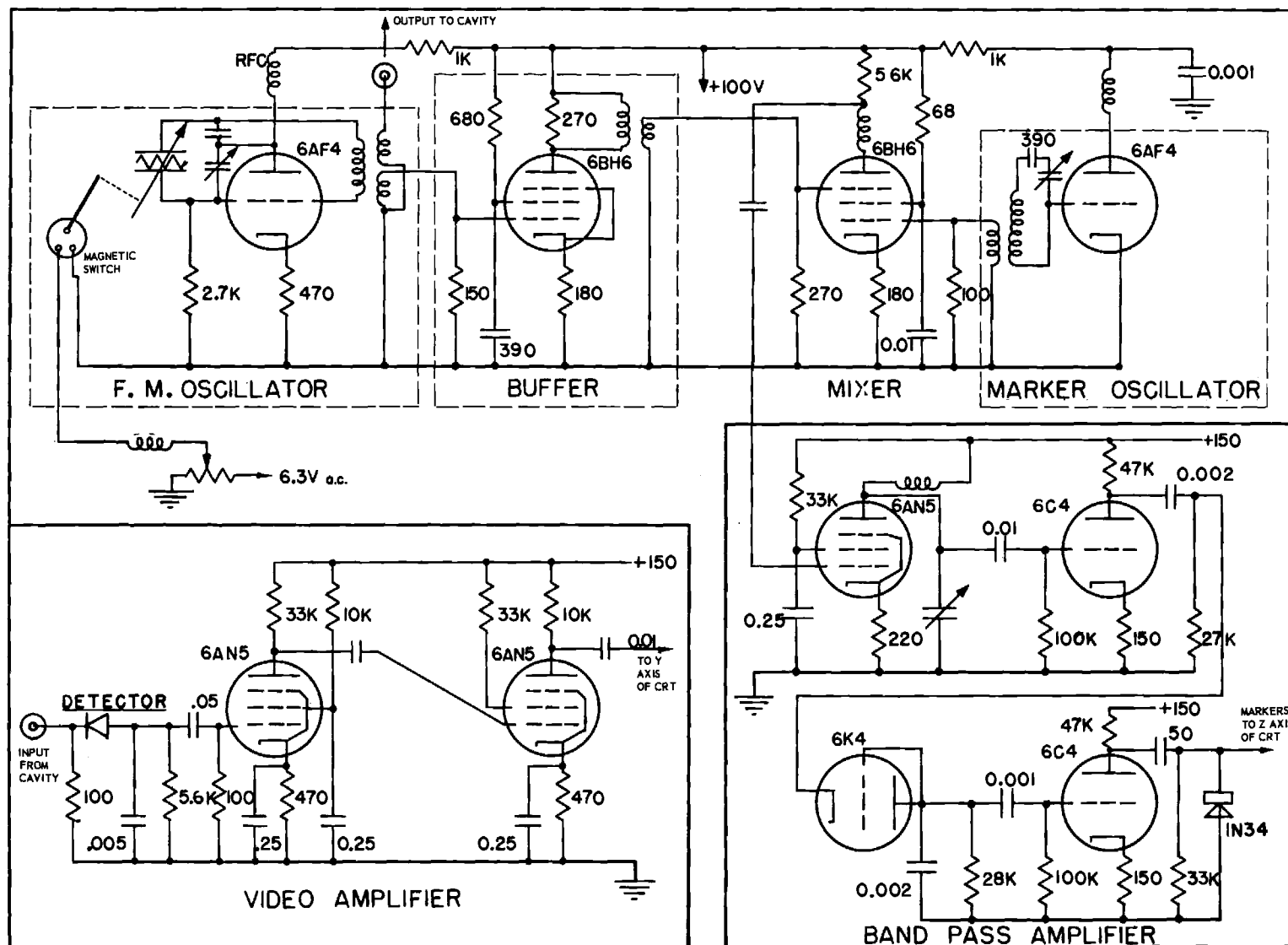


Figure 6.2. Schematic Diagram, Cavity Q Meter.

shown. The schematic is representative of components which have proved adequate to date.

Requirements for Obtaining Significant Measurements.

The measurement technique outlined in the introduction to this section is valid provided the linearity and non-frequency selectivity of circuit parameters is maintained. The most serious difficulty encountered is that of eliminating the impedances variations which occur in the transmission lines used for coupling purposes. It is often desirable to separate the cavity and Q-meter, an example of this condition occurs when the cavity is inserted in a heat chamber where its frequency versus temperature response can be conveniently attained. In this case several feet of coaxial cable are required to couple the cavity to the Q-meter. Unless the lines and their terminations are quite carefully matched the variable impedances reflected both into the oscillator and into the cavity may result in such adverse effects as frequency pulling of the oscillator and apparent distortion of the cavity response.

One method of sharply reducing these impedance variations is to place resistive attenuators in the line. The apparent mismatch due to an improper line termination may be considerably reduced. A 6 db. resistive pad, for instance, will reduce a 3:1 VSWR to the relatively satisfactory value of 1.3:1. However, certain disadvantages associated with the loss of voltage incurred may override the advantages accruing. The increase of coupling into the cavity required to compensate for this voltage loss appears disadvantageous on the basis of the analysis to follow. Resistive pads have not been used to date with the cavity Q-meters. In lieu thereof a semi-matched condition has been obtained by feeding the input line by a cathode follower whose output impedance very closely corresponds to the Z_0 of the line. The other end of the line may be matched in impedance at f_a , the resonant frequency of the cavity, if the impedance of the loop coupling into the cavity is also equal to Z_0 (at f_a). It is true that some mismatching effects occur at frequencies different from f_a , but the cathode follower partially isolates these effects from the oscillator. The cathode follower, itself, is coupled to the oscillators by a line which is very short and which is therefore essentially non frequency-selective.

The output line, that between cavity and detector, may also include a resistive attenuator or may be semi-matched by somewhat the same process. The coupling loop of the cavity is of such size as to provide an impedance of Z_o at f_a the detector input impedance is made very nearly equal to Z_o at all frequencies of interest by shunting it with an essentially pure conductance of proper value.

Q-Factors, Coupling Parameters, and External Loading.

It is convenient to begin an analysis of the quantities involved in measurement by reviewing the methods of representing the parameters of a cavity and of determining proper coupling values. These items were discussed in detail in the previous project ⁽¹⁾ and are briefly summarized here for convenient reference.

A quarter-wave coaxial resonator may be represented by the equivalent lumped parameters of Fig. 6.3.

The characteristic impedance Z_o of a coaxial line is given by:

$$Z_o = \frac{1}{2\pi} \sqrt{\frac{\mu_1}{\epsilon_1}} \ln(b/a) \text{ ohms} \quad (6.1)$$

where μ_1 , and ϵ_1 , are the permeability and permittivity of the medium between the inner and outer conductors.

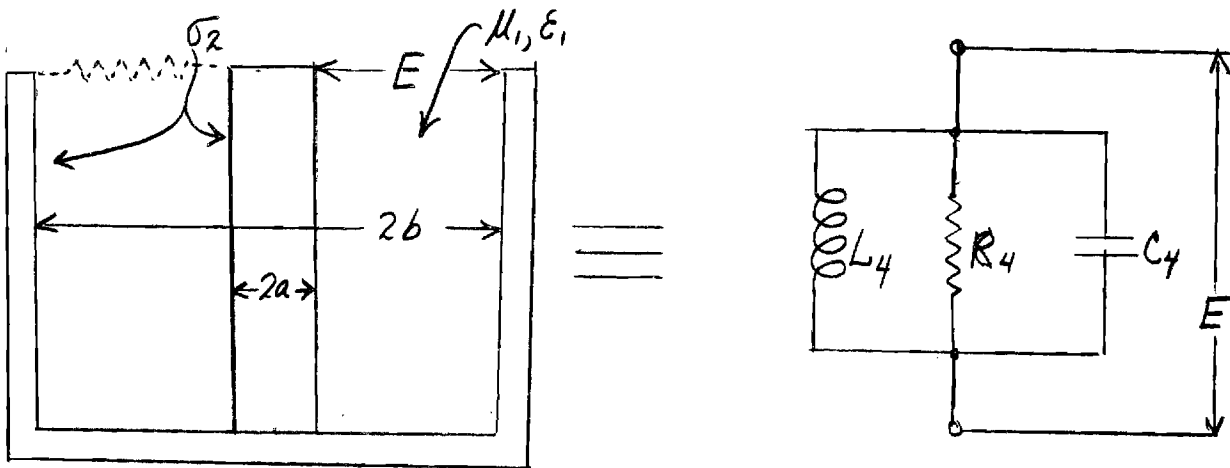


Figure 6.3. Quarter-Wave Coaxial Resonator

In terms of the equivalent circuit, Z_o is given by:

$$Z_o = \pi/l \sqrt{\frac{L_l}{C_l}} \text{ ohms} \quad (6.2)$$

The parameters of the equivalent circuit of the quarter-wave resonator in terms of line constants are given in the following expressions:

$$C_l = \pi/l Z_o \omega_a = x_o/2Z_o \text{ farads} \quad (6.3)$$

$$L_l = l Z_o / \pi \omega_a = 8x_o Z_o / \pi^2 \text{ henries} \quad (6.4)$$

$$R_l = Z_o / \lambda x_o \text{ ohms} \quad (6.5)$$

Equations 6.3, 6.4, and 6.5 give the element values of the equivalent circuit which approximates the open-end impedance of the resonator. This approximation is excellent in the region of antiresonance but fails at higher and lower frequencies.

The parameters listed in these formulas are defined as follows:

$$\omega_a = \pi \sqrt{2x_o} = 2\pi f_a = 1/\sqrt{L_l C_l} \text{ radians/sec} \quad (6.6)$$

$$v = 1/\sqrt{\mu_1 \epsilon_1} \text{ meters/sec} \quad (6.7)$$

$$x_0 = \lambda_a/4 \text{ meters} \quad (6.8)$$

and

$$\alpha = 1/2 \sqrt{\frac{\pi f \mu_2 \epsilon_1}{\sigma_2 \mu_1}} (1/b + 1/a) \frac{1}{\ln(b/a)} \text{ nepers meter} \quad (6.9)$$

The Q, or selectivity of the resonator is given by:

$$Q = R_4/\omega_a L_4 = R_4 \omega_a C_4 = \pi f_a / \alpha v \quad (6.10)$$

Although various means of coupling can be utilized, the present method employed is as shown in Figure 6.4.

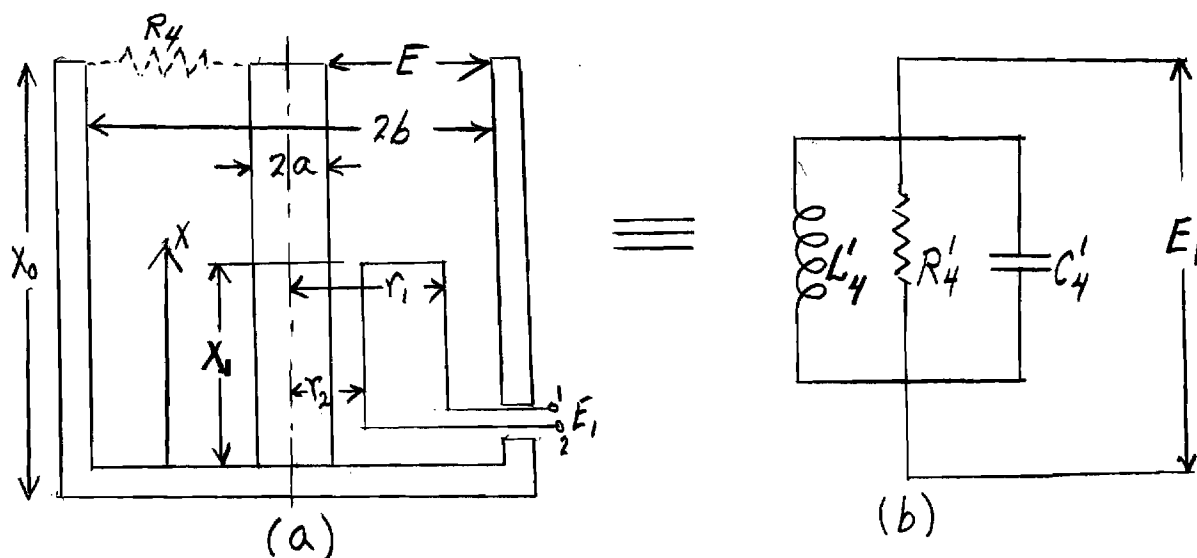


Figure 6.4. Coupling Method.

The equivalent parameters of the cavity, when transformed by the impedance ratio of cavity to loop, are represented in the right section of the figure.

The impedance at the loop terminals may be determined by assuming a peak current, I_m , to be flowing at the short circuit end of the cavity.

From the known sinusoidal distribution of the magnetic field due to this current, the voltage induced in the loop and at the open end of the cavity may be determined. If this is carried through there is obtained for these voltages the expressions:

$$E_{\max} = \frac{\omega \mu_1 I_m x_o}{\pi^2} \sin\left(\frac{\pi}{2}\right) \ln(b/a) \quad (6.11)$$

$$E_{l \max} = \frac{\omega \mu_1 I_m x_o}{\pi^2} \sin\left(\frac{\pi}{2} \frac{x_1}{x_o}\right) \ln \frac{r_2}{r_1} \quad (6.12)$$

Equating E^2/R_L to E_l^2/R_L'

we obtain:

$$R_L' = R_L \left[\frac{\ln b/a}{\sin\left(\frac{\pi x_1}{2x_o}\right) \ln \frac{r_2}{r_1}} \right]^{-2} \quad (6.13)$$

This relationship given in (6.13) is convenient in calculating either the equivalent impedance of a coupling loop of known size or conversely of determining the required length of the coupling necessary to provide a desired impedance. A simple example will indicate the order of magnitude of several of the above quantities. The cavity under consideration consisted of silver-plated conductors with $2b = 6.3$ cms, $2a = 13$ cms, $x_o = 25$ cms. For this resonator $R_L = 1,2000,000$ ohms, $L_L = 0.067$ microhenries, $C_L = 4.3$ micro micro farads, $Z_o = 100$ ohms, $\alpha = 3.4 \times 10^{-4}$ nepers/meter, and $Q = 9300$. This cavity was coupled to the cavity Q meter by coaxial cables of $Z_o = 180$ ohms. Utilizing equation (4.13) it is found that a loop length of approximately 0.8 centimeters will provide an impedance, at f_a , of about 180 ohms. The input and output coupling loops were thus made 0.8 centimeters long to assure the semi-matching discussed earlier in this section.

Loaded and Unloaded Q's.

The cavity, complete with input and output coupling loops may be conveniently represented by Figure 6.5a. The coupling loops are replaced by ideal transformers having impedance transformations of N_1^2 and N_2^2 respectively. If the leakage inductance of the loops is neglected as being negligible, than an equivalent lumped equivalent of the cavity, valid at f_a , is shown in Fig. 6.5b.

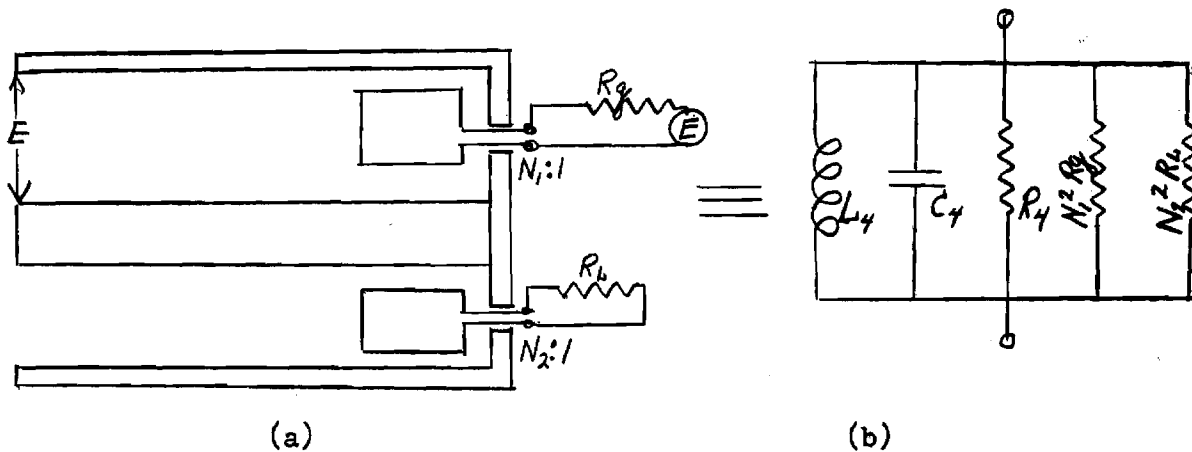


Figure 6.5. Equivalent Circuit of Cavity and Coupling Loops.

The loaded and unloaded Q's of the cavity can be now defined in terms of the parameters of Figures 6.3 and 6.5.

$$Q_u = \text{unloaded } Q = \frac{R_{L_4}}{\omega_a L_4} \quad (4.14)$$

We can likewise define a loaded Q by:

$$Q_L = \text{loaded } Q = \frac{R_o}{\omega_a L_4} \quad (6.15)$$

where R_o , from Fig. 6.5b is given by:

$$R_o = \frac{1}{\frac{1}{R_{L_4}} + \frac{1}{N_1^2 R_g} + \frac{1}{N_2^2 R_L}} \quad (6.16)$$

from which it is evident that

$$Q_u = Q_L (R_4/R_o) \quad (6.17)$$

If R_g and R_L are chosen to equal the Z_o of the coupling lines, and further if N_1 and N_2 are each chosen so that

$$\frac{1}{N_1^2} R_4 = Z_o = \frac{1}{N_2^2} R_4$$

then

$$R_o = 1/3 R_4 \text{ and } Q_u = 3 Q_L.$$

This is the condition which is established if the matched conditions are obtained.

The obvious disadvantages of the method of matching utilized here is that the impedance of the input coupling loop varies rapidly near f_a and that this variation is reflected to the cathode follower output and in reduced magnitude to the oscillator output. However, two distinct advantages appear to be gained by not using attenuators with a possible total loss of 25-30 db. The first is that the size of the coupling loops into the cavity may be greatly reduced (for example, when attenuators totaling 30 db. were used the input loop was required to be 3 cms long whereas a length of only 0.8 cm was used in the absence of attenuators). The second is that the oscillator may be much more lightly coupled to the line than was possible when high losses were present.

As time permits, it is planned to experimentally compare the action and results of the two systems by making a large number of equivalent tests. In the meantime, results obtained by the semi-matched conditions will be reported.

VII. VERIFICATION OF RELATIONSHIPS INVOLVING SUSCEPTANCE SLOPE AND SELECTIVITY

In the final report of Project 171-118, relationships involving the dimensionless factor Q and the reactance slope of linear high Q passive networks were determined. ⁽¹⁾ The reactance slope was computed at the resonant frequency of the network. Q was defined on the basis of the natural behavior of the circuit at the resonant frequency and was independent of any input frequency ω . It was shown analytically that, for all high Q networks, a knowledge of this merit factor Q was entirely equivalent to a knowledge of the slope of the reactance curve computed at a resonant frequency of the network, or alternatively, equivalent to the susceptance slope at an antiresonant frequency. The object of this work is the experimental verification of the above statement by means of a typical oscillatory network.

Since the prime interest is in the design of practical oscillator circuits which usually operate at parallel resonance, it is convenient to deal with the susceptance slope rather than the reactance slope. In any case, one can be extended to the other by the principle of duality.

For all high Q passive networks, the susceptance slope at ω_a is

$$\left. \frac{dB}{d\omega} \right|_{\omega_a} = \left. \frac{2QG}{\omega} \right|_{\omega_a}, \quad (7.1)$$

where ω_a is the antiresonant frequency, and G and B the conductance and susceptance of the network respectively. In practical oscillators, frequency instability is inversely proportional to the susceptance slope, ie.

$$\frac{d\omega}{\omega} = K' \frac{d\omega}{dB}. \quad (7.2)$$

The frequency instability K resulting from changes in tank capacitance is given by the equation

$$K = \frac{d\omega}{\omega} \bigg/ \frac{dc}{c}, \quad (7.3)$$

where $d\omega/\omega$ represents an incremental change in frequency, and dc/c an incremental change in tank capacitance.

The substitution of equation (2) into (3) yields

$$K = K' \frac{\frac{d\omega}{dB}}{\frac{dc}{c}}. \quad (7.4)$$

Hence, to verify equation (1), it is only necessary to verify equation (4) with $d\omega/dB$ replaced by equation (1). That is,

$$K = K' \frac{\frac{\omega}{2QG}}{\frac{dc}{c}} \bigg|_{\omega = \omega_a},$$

or

$$K = K'' \frac{1}{QG} \bigg|_{\omega = \omega_a} = K'' \frac{R}{Q} \bigg|_{\omega = \omega_a}. \quad (7.5)$$

Hence, essentially, it is necessary to show that the frequency instability K is inversely proportional to the Q and the conductance of the network. In other words, the verification of the above statement would indicate that the susceptance slope, and hence the frequency controlling ability of a network, depends upon the impedance level and selectivity rather than upon the configuration.

The Clapp Circuit.

The Clapp oscillator ⁽⁵⁾ in Fig. 7.1a was selected for study because of its unusual stability over a wide range of element values. The

adjustments are noncritical, and the addition of the series tuning capacitor in the tank circuit increases the flexibility of the system for purposes of experimentation.

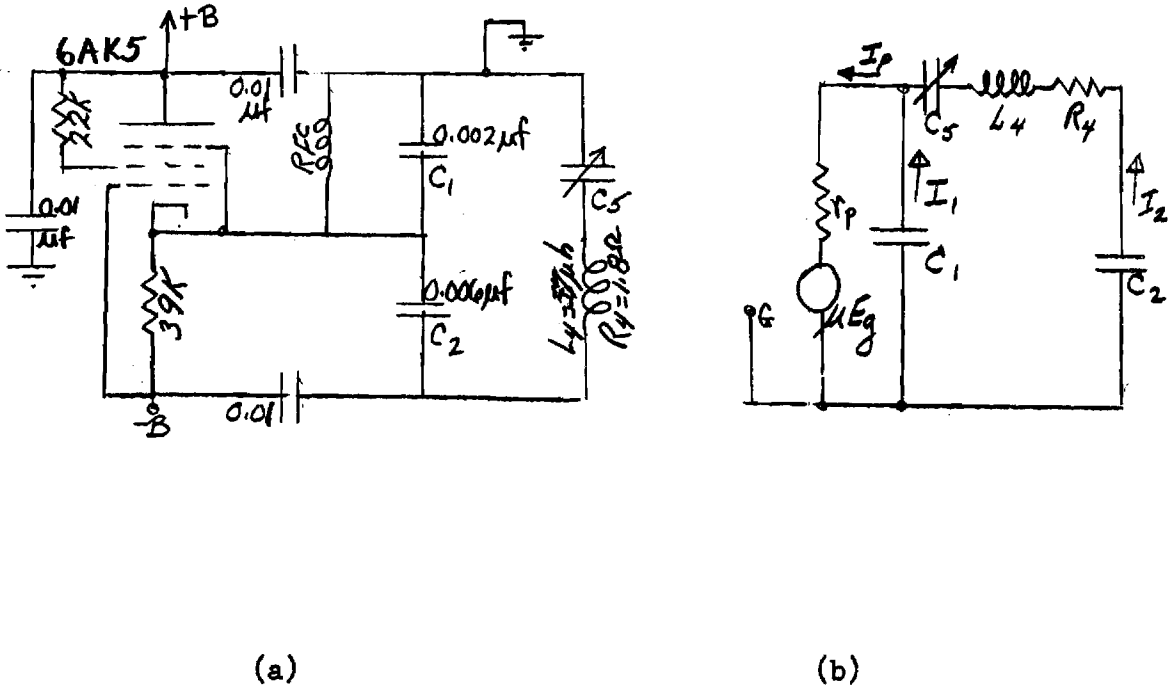


Figure 7.1. The Clapp Oscillator Circuit.

Fig. 7.1b is the equivalent circuit of the Clapp oscillator. A mathematical analysis based on the equivalent circuit yields the following results:

$$\omega = \left(\frac{1}{C_3 L_4} + \frac{1}{C_1 L_4} + \frac{R_4}{C_1 L_4 r_p} \right)^{\frac{1}{2}}, \quad (7.6)$$

$$\omega = \omega_0 \left[1 + \frac{R_4}{r_p} \left(\frac{C_2 C_5}{C_1 C_2 + C_1 C_5 + C_2 C_5} \right) \right]^{\frac{1}{2}}, \quad (7.7)$$

and

$$g_m = \frac{R_4 (C_1 C_2 + C_1 C_5 + C_2 C_5)}{C_5 L_4} + \frac{C_2}{r_p C_1}. \quad (7.8)$$

In most cases, especially when pentodes are used,

$$\frac{C_2}{r_p C_1} \ll \frac{R_4 (C_1 C_2 + C_1 C_5 + C_2 C_5)}{C_5 L_4},$$

and

$$g_m = \frac{R_4 (C_1 C_2 + C_2 C_5 + C_1 C_5)}{C_5 L_4}. \quad (7.9)$$

In equations (6) to (9);

$$C_3 = \frac{C_2 C_5}{C_2 + C_5},$$

ω = angular frequency of oscillation,

g_m = transconductance, and

ω_0 = natural resonant frequency of resonant circuit of Fig. 7.1b.

The Clapp oscillator using a W.E. 6AK5 was constructed with element values as shown in Fig. 7.1a. The operating frequency was to be in the neighborhood of one megacycle. The coil L_4 consisted of 30 turns of No. 20 P.E. wire wound on a 3 inch-diameter coil form. The inductance and the effective resistance R_4 of the coil were measured with a Q-meter (B.R. 160 - A) at a frequency of 1.168 Mc and found to be 57 ohms and 1.85 ohms respectively. C_5 consisted of a fixed mica condenser C_p (= 413 μmf) in parallel with a variable capacitor C'_5 (range: 19 μmf - 400 μmf). The frequency of the oscillator, measured with a BC - 221 frequency meter, was found to be 1.168 Mc, which, compared to the calculated value of 0.917 Mc, shows a deviation of 21.5 percent.

Modified Clapp Oscillator.

As a further check on the mathematical analysis of the Clapp circuit, it was desired to measure the operating angle θ (which is half the

progressively varying the value of C_1 . The effects on the oscillator frequency due to incremental changes in plate voltage, C_1 and C_2 were recorded. The values of K were also calculated by means of equation (3).

These preliminary readings show the following results:

- (i) There was no appreciable change of frequency as the plate supply voltage was varied from 180 volts to 120 volts.
- (ii) There was an indication that there exists an optimum value of n which corresponds to a minimum value of K .

A more careful investigation of K was necessary to determine the optimum value of n , and hence additional readings were made. As before, n was varied, but this time the bias E_c was kept as constant as possible. n was varied from 50 to $1/30$, and the optimum value of n was found to be in the neighborhood of $\frac{1}{2}$. This was found to be a reasonable value of n to work with. The next step consisted of keeping the impedance level fixed and studying the behavior of K as Q varied.

With $n = \frac{1}{2}$, and Q varying in arbitrary steps (by adding series resistance to the coil), readings were made to determine corresponding values of K . The supply voltage E_b , the grid bias E_c and the oscillator frequency were held constant in an attempt to maintain a constant impedance level. This initial attempt to keep the impedance level constant was unsuccessful, and a study was made to determine what parameters must remain constant in order to maintain a constant impedance level.

Determination of Parameters Governing Impedance Level.

A series of impedance measurements were made with E_b , E_c , E_p (r-f voltage across C_1) and I_p (tank input current) held constant. This was accomplished by careful adjustment of C_1 and C_2 and of the variable capacitor C_5 . These impedances were measured with a 516-C, G.R. high-frequency bridge. A piece of shielded wire about one foot long was used to correct the impedance to the "unknown terminals" of the bridge. (See Fig. 7.3a.

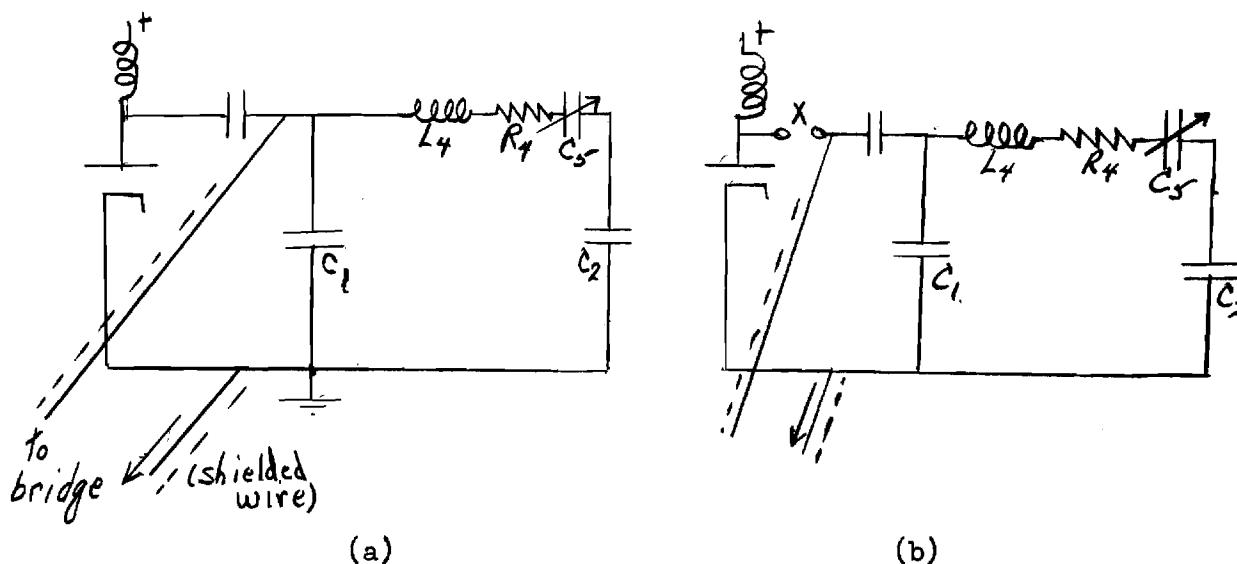


Figure 7.3. Measurement of Parameters.

Readings were made first with the supply voltage on and then with it off. The two readings thus made did not differ by any significant amount. Further readings were made with the impedance connected as shown in Fig. 7.3b, the plate circuit being broken at the point x, and the plate supply disconnected. C_1 and C_2 were replaced by variable linear capacities, (Type G.R. 539-B). Several trial runs indicated that the impedance level did remain constant under the prescribed conditions. However, this was an extremely tedious and time-consuming procedure because three variables in the tank circuit are involved. It was found that the variable condenser C_5 could be replaced by an equivalent fixed condenser equal to 700 μf without upsetting the prescribed conditions significantly. The elimination of this one variable simplified the procedure considerably without greatly sacrificing accuracy. Five sets of readings made in this manner and are recorded in Table I. Although I_p is no longer constant, its variation from the initial value is not significant.

Derivation of Input Impedance Z.

A rough check can be made on the measured values of impedance and frequency by deriving the mathematical equations for the impedance looking into the plate tank circuit in terms of the circuit parameters.

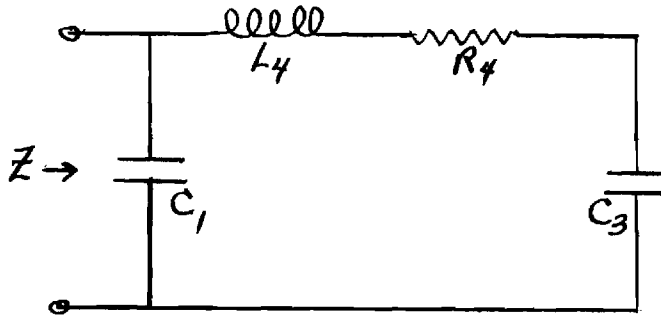


Figure 7.4. Parameters of Plate Circuit.

$$Y = j\omega C_1 + \frac{1}{R_4 + j \frac{\omega^2 C_3 L_4 - 1}{\omega C_3}} \quad (7.10)$$

From Fig. 7.4 it is evident that

$$\omega_a^2 = \frac{C_1 + C_3}{C_1 C_3 L_4} \quad (7.11)$$

Substituting (11) into (10)

$$Y \Big|_{\omega = \omega_a} = \frac{\omega_a^2 C_1^2 R_4}{\sqrt{1 + \omega_a^2 R_4^2 C_1^2}} \angle 90^\circ - \tan^{-1} \frac{1}{\omega_a C_1 R_4} \quad (7.12)$$

$$\text{or } Z \Big|_{\omega = \omega_a} = \frac{1 + \omega_a^2 R_4^2 C_1^2}{\sqrt{\omega_a^2 C_1^2 R_4^2}} \angle \tan^{-1} \frac{1}{\omega_a C_1 R_4} - 90^\circ \quad (7.13)$$

If $\omega_a^2 R_4^2 C_1^2 \ll 1,$

$$Z \Big|_{\omega = \omega_a} \approx \frac{1}{\omega_a^2 C_1^2 R_4} \angle \tan^{-1} \frac{1}{\omega_a C_1 R_4} - 90^\circ \quad (7.14)$$

Equation 10 shows that Z is inductive or capacitive depending upon whether $\omega^2 C_3 L_4$ is less or greater than unity.

TABLE I
IMPEDANCE MEASUREMENTS

C_1 (μpf)	C_2 (μpf)	$1/n$	R_4 (ohm)	f_o Measured	f_o Calculated Mc	Z Measured	Z Calculated
2570	5390	2.10	6.85	0.949	0.945	436 $\angle -7^\circ.5$	630 $\angle -6^\circ$
1910	4300	2.25	11.85	0.987	0.987	438 $\angle -11^\circ.9$	603 $\angle -8^\circ$
1340	3080	2.30	19.85	1.046	1.055	407 $\angle -11^\circ.7$	631 $\angle -10^\circ.1$
953	2392	2.51	34.85	1.112	1.135	491 $\angle -14^\circ.7$	616 $\angle -13^\circ.4$
314	992	3.16	101.85	1.401	1.580	552 $\angle -31^\circ.4$	1000 $\angle -17^\circ.7$

The above results show that the calculated values of oscillator frequency check closely with the measured values. With the exception of the 5th reading, where the Q is relatively low, the relationships between calculated and measured values of Z are consistent. The difference in the two sets of values is attributed to error in performing the bridge measurements, and more likely to the tolerance of R_4 which is an ordinary carbon resistor. Equation (7.14) shows that Z is inversely proportional to R_4 . The maximum deviation of the values of Z from its average value of 459 ohms (neglecting the 5th reading) is approximately 7 percent. Hence, for all practical purposes in the range of interest (high Q networks) the driving point impedance Z can be considered constant by keeping E_b , E_c , E_p , and I_p constant.

Relationships Between K , Q , and R .

Now that the parameters governing impedance level have been ascertained, it remains to verify equation 7.5 by first showing the existence of an inverse proportionality between K and Q when R is constant, and then showing that K varies directly with R when Q is fixed. For the first case where Q is the independent variable, Q was varied

by first increasing the effective resistance of the coil. This was accomplished simply by adding series resistance to the coil. Then Q was again varied by decreasing L_4 and holding R_4 constant. This was done in the following manner. The coil was tapped at four arbitrary points, and the inductance at each point was measured with the Q -meter. A rheostat was then added in series with the coil. Using the entire coil and with the rheostat completely out, the Q is determined. This Q is used as a reference. Then moving to the first tap on the coil, the rheostat is adjusted so that the Q -meter gives a new reading of Q which is decreased in proportion to the decrease in L_4 . This new value of Q is the Q of the coil at the first tap with the effective resistance remaining substantially the same as before. This procedure was repeated for the remaining taps.

Table II shows the results of the first of three runs. The impedance was maintained at a fixed level (as far as possible) and K was measured as the Q was decreased in arbitrary steps by adding resistance in series with the coil. All r-f bridge measurements were made at the frequency of oscillation. The plate supply for this and other runs was regulated at 180 volts. "Incremental" changes in C_1 and C_2 were affected by shunting C_1 and C_2 with a 10 μ pf condenser. (For run three, this was changed to 20 μ pf.) A plot of K versus Q in Fig. 5 shows clearly the inverse relationship between the two parameters.

Run two, as tabulated in Table III differs from the previous run only in the manner in which the Q of the coil was varied. This time Q was decreased by decreasing the inductance of the coil. Again, the plot of K against Q shows that K is inversely proportional to the Q at a constant impedance level. In the final run, the Q is held constant while the impedance level is arbitrarily changed. The curves of K versus $R(= \frac{1}{G})$ show a direct proportionality between the two parameters. Thus, the results of all three runs support the validity of equation (7.5). This in turn answers the validity of the equation

$$\left. \frac{dB}{d\omega} \right|_{\omega_a} = \frac{2QG}{\omega} \left|_{\omega_a} \right. \quad (1)$$

TABLE II

C ₁ unf	C ₂ unf	f _a Mc	f _{dc₁} Mc	f _{dc₂} Mc	R _L ohm	L _L uh	Q	R ohm	K	
									K ₁	K ₂
2530	4790	0.9734	0.9731	0.9733	6.85	57	51	436	0.090	0.054
1910	3710	1.0072	1.0067	1.0070	11.85	57	35	433	0.095	0.074
1300	2680	1.0672	1.0663	1.0668	19.85	57	20	455	0.114	0.106
950	2060	1.1369	1.1352	1.1364	34.85	57	12	460	0.144	0.091
307	873	1.4258	1.4190	1.4235	101.85	57	5	503	0.145	0.137
TABLE III										
4060	6000	0.8904	0.9801	0.8902	2	57.2	160	370	0.059	0.050
3500	5080	1.0356	1.0352	1.0353	2	43.5	141	372	0.070	0.078
3240	4520	1.2264	1.2259	1.2260	2	32.0	123	344	0.076	0.074
2880	4440	1.3958	1.3948	1.3951	2	25.2	111	334	0.101	0.105
1965	3540	2.0376	2.0350	2.0356	2	12.9	83	239	0.126	0.177
TABLE IV										
5500	6700	0.9094	0.9092	0.9093			121	204	0.079	0.036
4600	6140	0.9185	0.9182	0.9184			122	606	0.072	0.055
4040	5800	0.9296	0.9292	0.9294			124	424	0.080	0.056
3340	5580	0.9408	0.9403	0.9406			125	562	0.083	0.059
3160	5400	0.9486	0.9480	0.9484			126	678	0.094	0.066

Note: f_{dc₁} = frequency with incremental change in C₁

f_{dc₂} = frequency with incremental change in C₂

$$Q = \frac{2\pi f_a L_L}{R_L}, \quad K_1 = \frac{df_1}{f_a} \bigg/ \frac{dc}{C_1}, \quad K_2 = \frac{df_2}{f_a} \bigg/ \frac{dc}{C_2}$$

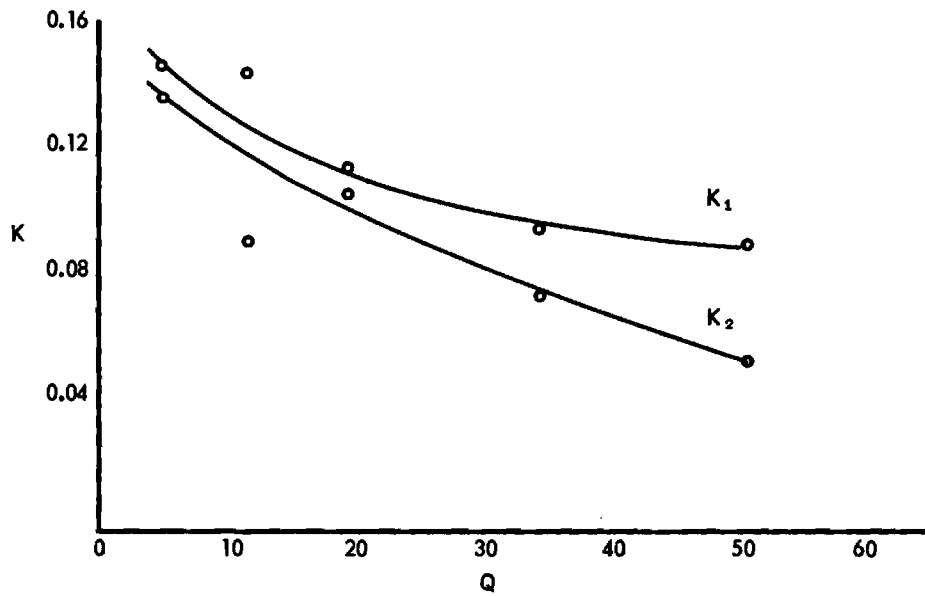


Figure 7.5 (a). Variation of K versus Q at Constant Impedance Level.

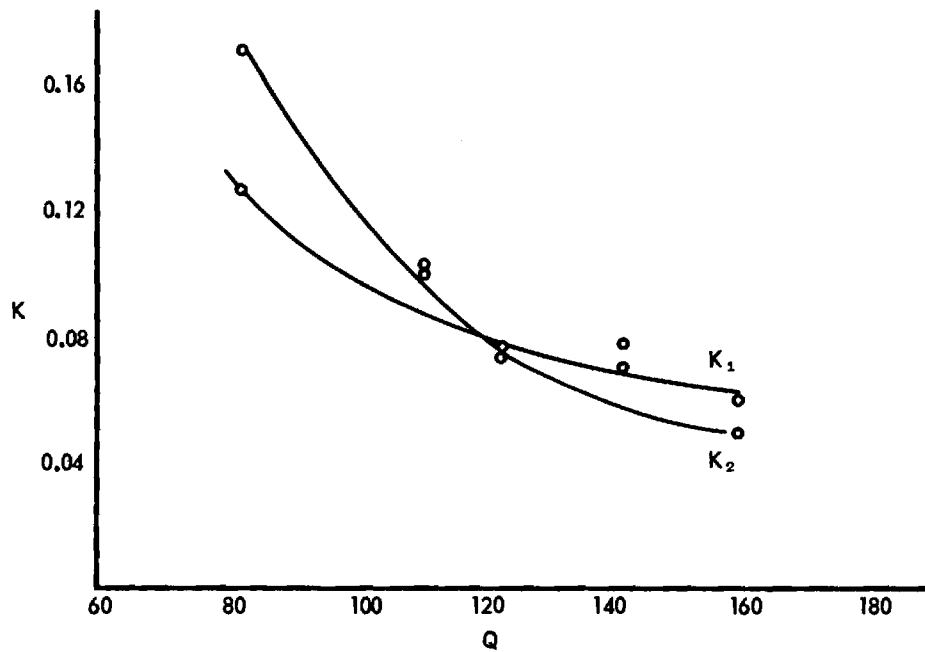


Figure 7.5 (b). Variation of K versus Q at Constant Impedance Level.

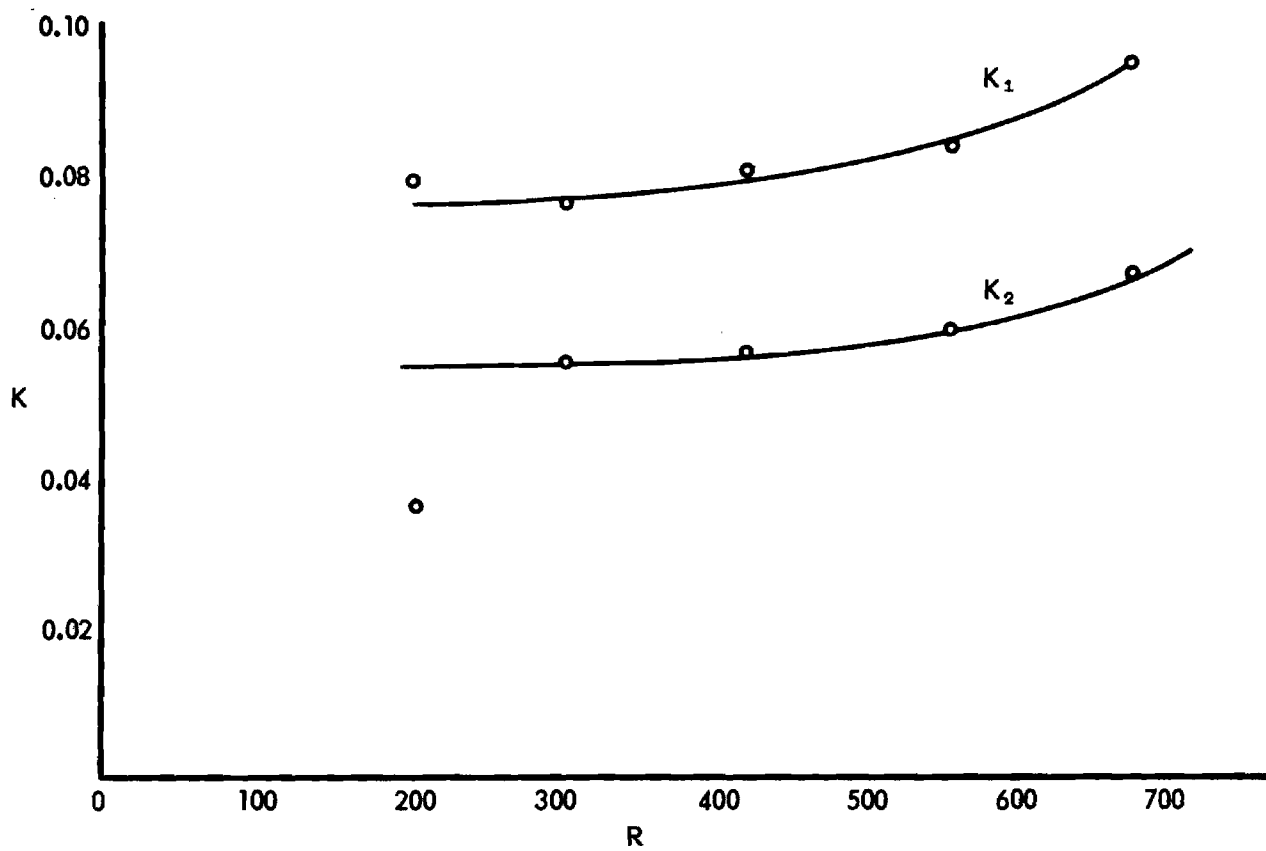


Figure 7.5 (c). Variation of K Versus R at Constant Q.

CONCLUSION

Equation (1) above, and its dual, namely,

$$\left. \frac{dX}{d\omega} \right|_{\omega_r} = \left. \frac{2QR}{\omega} \right|_{\omega_r} \quad (15)$$

are valid for all high Q passive networks. Hence, for any admittance function, the specification of the susceptance slope $dB/d\omega$ is entirely equivalent to the specification of Q when the conductance G is known. Or, conversely, if Q and G are specified at a frequency ω_a , then $\left. \frac{dB}{d\omega} \right|_{\omega = \omega_a}$ is unique and independent of any particular network function. Also, this experiment has shown that the frequency instability due to incremental changes in circuit elements, such as those resulting from random changes in tube and tank capacitances, is inversely proportional to the susceptance slope $dB/d\omega$. This property makes equation (7.1) (or equation 7.15) particularly useful in the design of practical oscillators. Hence, the conductance and the selectivity of a network, and not its configuration, are the governing factors of frequency stability. It follows then, in the design of oscillators with high frequency stability in mind, the network configuration chosen should be one that not only produces a suitable conductance but as large a value of Q as possible.

VIII. CONCLUSIONS

Cavities composed of ceramic materials appear to have good possibilities of being acceptable resonators, particularly if their temperature coefficient of expansion is extremely low. Although there are numerous difficult and time-consuming processes associated with their construction, the attractive feature of temperature insensitivity may well warrant acceptance of the severe problems of fabrication.

The Cavity Q Meter shows considerable promise in permitting tests of the cavity as a passive resonator rather than as an active element of an oscillator.


Preliminary investigations have yielded some encouraging indications that frequency control by high order overtones in quartz crystals may be feasible.

IX. PROGRAM FOR NEXT QUARTER

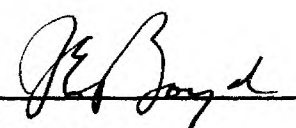
The investigation of cavities will be continued. Emphasis will be directed toward the construction of cavities designed to achieve small frequency deviation by further processes of compensation and also by the utilization, as center conductors, of recently acquired Stupalith rods. Frequencies in the region of 500 Mc will be generated by oscillators and/or the cavity Q-meter, in order to investigate cavity characteristics in that frequency range. Numerous further tests will be conducted on the resonators constructed during the period of this report and the results will be made available in the next report.

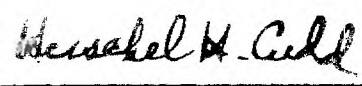
The investigation of crystals will be continued with emphasis on extending the frequency range at least to 300 Mc during the next quarter. The responses of both mounted and unmounted crystals will be studied at these higher frequencies. An attempt will be made to construct a test oscillator controlled by crystal absorption rather than by the transfer action herein described.

Respectfully submitted


Vernon Crawford
Project Director

Approved:


J. E. Boyd
Head Physics Division


Herschel H. Cudd
Acting Director
State Engineering Experiment Station

X. IDENTIFICATION OF KEY TECHNICIANS

This project is under the direction of Dr. Vernon Crawford who devotes approximately one fourth time to this work. Dr. Crawford is Associate Professor of Physics; he received his Doctor's degree from the University of Virginia and specializes in electromagnetic phenomena. He worked on nuclear quadrupole resonances in connection with station project 171-118, "Investigation of Frequency Control above 150 Mc."

Mr. Donald W. Fraser is serving as assistant project director. He is Assistant Professor of Electrical Engineering at Georgia Tech and holds the degree of Master of Science in Electrical Engineering from that the same institution. He worked on station project 131-45, "High-Frequency Crystal Controlled Oscillators," devoting approximately one-fourth time thereto. His other experience includes five years of electronic testing and research in the U.S. Navy. Mr. Fraser is currently devoting two thirds time to this project and will devote full time during the summer months.

Mr. James C. Sellers joined the project as Electronics Technician at its onset. He is currently devoting three quarters time to the project. Mr. Sellers previously was engaged for eight years in nuclear instrumentation with AEC at Oak Ridge, Tennessee where he had extensive experience as a technician in design, assembly, and testing of electronic circuits.

Mr. James C. Hogg, Jr., Assistant Research Professor, devotes approximately one-fourth time to this project. Mr. Hogg holds the degree of Master of Science in Electrical Engineering from the Georgia Institute of Technology. Mr. Hogg has had extensive experience in circuit design and oscillators both in the industrial and the research field. He was employed on a full time basis on the S.C.E.L. projects "High Frequency Crystal Controlled Oscillator Circuits" and "Investigation of Frequency Control above 150 Mc."

XI. BIBLIOGRAPHY

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Georgia Institute of Technology
ENGINEERING EXPERIMENT STATION
Atlanta, Georgia

PROGRESS REPORT NO. 2

PROJECT NO. 229-198

PRECISION FREQUENCY CONTROL TECHNIQUES
(500 Mc and Higher)

By

VERNON CRAWFORD AND DONALD W. FRASER

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CONTRACT NO. DA-36-039-sc-42590

DEPARTMENT OF THE ARMY PROJECT: 3-99-11-022
SIGNAL CORPS PROJECT: 33-142B

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MAY 1, 1953 TO AUGUST 1, 1953

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ENGINEERING EXPERIMENT STATION
Atlanta, Georgia

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PROJECT NO. 229-198

PRECISION FREQUENCY CONTROL TECHNIQUES
(500 Mc and Higher)

By

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I. PURPOSE

The purpose of this project is threefold: (a) to continue work on the stabilization of oscillators between 500 and 3000 Mc, using cavity resonators, (b) to investigate any new phenomena of resonance that occur in the range of 500 to 3000 Mc and which may show promise of some success, and (c) to undertake any other investigations which may arise during the course of the work outlined in (a) and (b) above, or which may be mutually agreed upon between the Contractor and the Contracting Office or his representative.

By agreement with the sponsor, investigations of resonances below 500 Mc may be prosecuted as preliminary steps in determining the feasibility of frequency control by the phenomena under study. In addition, cavity resonators previously under construction and designed to provide control of frequencies below 500 Mc may be completed and tested as aids in perfecting measurement techniques which will be later applied to the 500 Mc and above range of frequencies.

II. ABSTRACT

A temperature-compensated cavity using an outer conductor of brass and an inner conductor of silver-plated Pyrex has been constructed and has been given extensive tests. This resonator, operating at a frequency of 300 megacycles, has exhibited an average frequency-versus-temperature change of about 0.5 parts per million per degree centigrade over a temperature range of seventy five degrees centigrade.

A cavity has been constructed which utilizes a ceramic, Stupalith, having a claimed small (approximately zero) coefficient of expansion. Problems arising during silver-plating and during final assembly of the completed resonator have been discussed in detail. Further data on the electrical characteristics must be accumulated before firm conclusions can be obtained.

Cavity-controlled oscillators operating in the 500 megacycle range have been constructed and tested. In these oscillators the cavity serves as a reactive element. Satisfactory cavity control is not difficult to obtain when the tube is mounted directly on, or in, the cavity but has proved difficult when a length of transmission line separates cavity and tube. Instabilities as small as 0.2 parts per million per volt change in anode potential have been obtained; instabilities which are on the average not worse than one part per million appear reasonable. These compare favorably with instabilities of twenty or more parts per million in the absence of cavity control.

Further investigations of the high-order overtone responses of quartz crystal resonators have shown that some crystals may be excited at overtones as high as the fifty-ninth, and that the responses of various crystals are virtually independent of holder capacitance and of the Q of the holder. The magnitude of response, however, decreases with the order of overtone.

III. CONFERENCES AND CONVENTIONS

The Frequency Control Symposium held at Asbury Park, New Jersey, May 18-20, 1953, under the auspices of the Signal Corps was attended by Mr. Fraser of this project. He participated in the symposium by presenting a paper entitled "Precise Frequency Control above 150 Megacycles". This paper summarized many of the developments achieved during the calendar year 1952 and discussed future plans for the present year.

On May 21, after the conclusion of the Symposium, Mr. Fraser met with representatives of the Signal Corps at Squier Signal Laboratory to discuss further aspects of the work being conducted under this project. During this conference the point was advanced that time and personnel limitations would render an experimental investigation of the whole frequency range of 500 to 3000 megacycles impractical if not impossible. It was thereupon tentatively agreed that experimental investigations might be limited to frequencies of 500 to 1000 megacycles but that some theoretical investigations of the upper range should be conducted and reported upon. In addition it was agreed that the investigation of the overtone responses of quartz crystal resonators should continue at the highest practicable frequency.

IV. COAXIAL CAVITY RESONATORS

Introduction

During the period of this report further efforts have been directed toward construction of coaxial cavity resonators whose resonant frequencies are little affected by changes in ambient temperature. Two basically distinct methods of construction have been utilized in efforts to achieve the desired goal. In one method two dissimilar materials were used in the process of cavity construction. The outer conductor consisted of silver-plated brass; the inner conductor was made of Pyrex glass with a portion of its length silver-plated to provide the necessary electrical conductivity. The different coefficients of thermal expansion of the two conductors were balanced out by a compensating device. This cavity will be referred to as the Compensated Brass cavity. In the other method the cavity consisted entirely of a ceramic with low expansion characteristics. Silver-plating of all active electrical surfaces was provided.

Both of these basic methods were mentioned in a previous report. ⁽¹⁾ However, at that time the construction of a satisfactory resonator of either type had not been completed. Details are now available on a compensated cavity which has been constructed and which has undergone extensive testing. The data indicate that satisfactory compensation for unlike coefficients of expansion may be achieved, and that a relatively high order of temperature stability may be realized. The next portion of this section of the report discusses this resonator in detail.

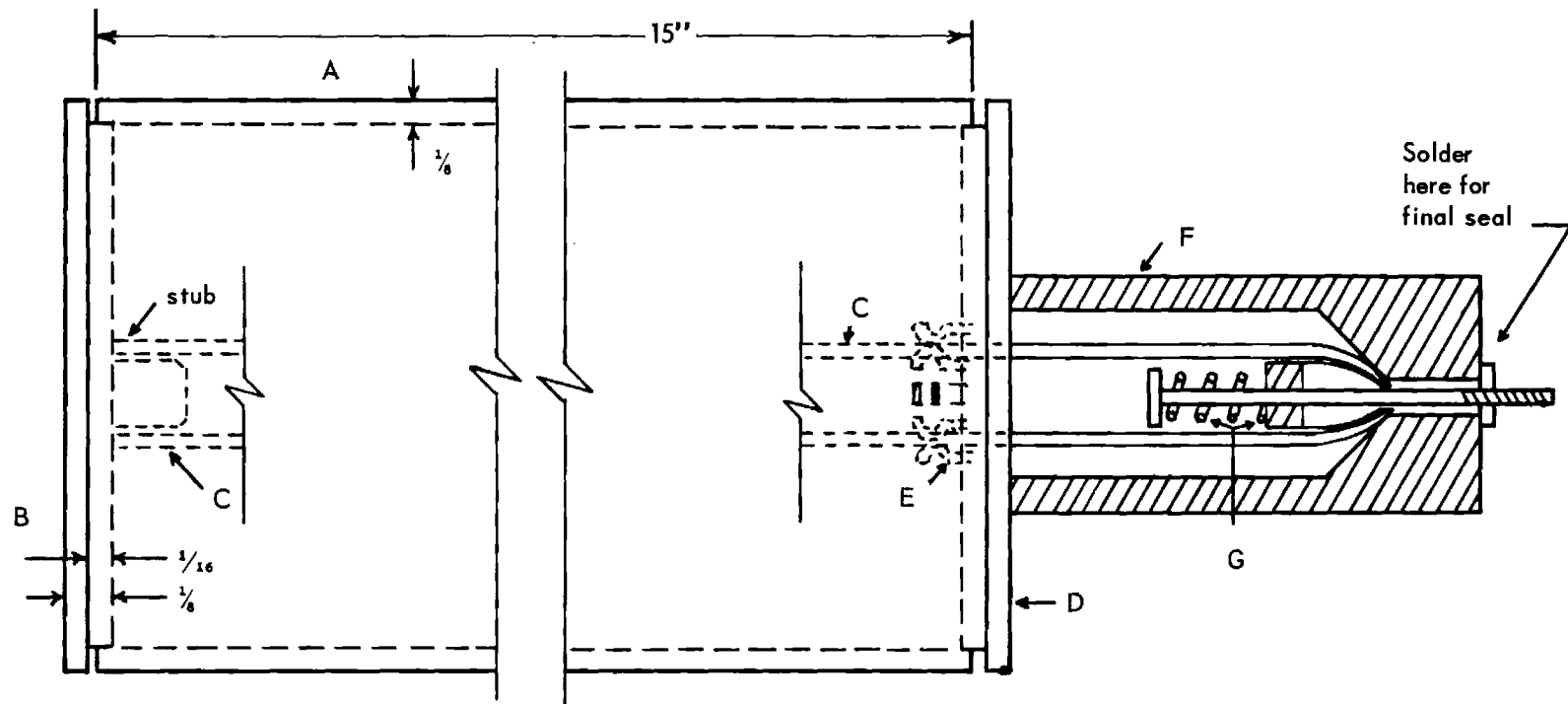
Ceramic resonators have been in process of construction for some time and one such unit has just been completed. A similar resonator, designed for a higher frequency range, is nearing completion. The ceramic material, Stupalith ⁽²⁾ was obtained on special order in the form of tubing having an inside diameter of approximately one-and-three-quarters inches, and of rods of one-half inch diameter. The rods and tubing have to be subjected to a somewhat lengthy finishing process in order to achieve a silvered coating of satisfactory conductivity.

Details of steps in the process are described in the last part of this section.

Compensated Brass Resonator

The temperature compensated brass resonator described in the previous report ⁽¹⁾ has been slightly modified and has been subjected to extensive tests. The principal changes consisted of substitution of Pyrex glass in place of Vycor glass, and of change of dimensions in the compensating section. Brass exhibits a temperature coefficient of expansion of about twenty parts per million per degree centigrade (ppm/°C) while Pyrex has a coefficient of approximately three parts per million. Compensation can be achieved if a piece of brass $3/20$ as long as the Pyrex controls the lateral movement of this tubing. This situation is illustrated in Figure 4.1. The pressure sealing cap, F, is composed of brass and by proper dimensioning can serve as the compensation control. The figure shows that the active electrical length of the center conductor is 24.5 centimeters. Exact compensation for its expansion should, in theory, be realized if that portion of this Pyrex within the brass seal is $3/20$ of 24.5 centimeters. This product yields a figure of 3.67 centimeters; in the actual construction the tube insertion depth turned out to be 3.75 centimeters.

The fact that the compensation section is slightly longer than the calculated value, coupled with the condition that some pieces of brass exhibit a coefficient of expansion slightly lower than 20, would indicate the possibility that this cavity might be overcompensated. In the absence of compensation the frequency of resonance decreases with rising temperature because of the increased length of the center conductor. Over-compensation, then, should produce resonant frequencies that increase with rising temperature. This phenomenon was, in fact, observed in certain cases. However, there is an added parameter affecting the frequency versus temperature characteristics. The factor involved is the ratio of area to mass existing in different portions of the resonator. Clearly this ratio is different in the heavy-walled cap from that in the thin-walled resonator proper. During slow rates of change of ambient temperature



Assembled view, consisting of following units:

- A. Hollow Tubing 15" long, $1\frac{3}{4}$ " O.D., $1\frac{5}{8}$ " I. D. (Brass)
- B. End Plate, $\frac{1}{8}$ " Brass with stub support for Pyrex tubing
- C. Pyrex tubing, silver plated 24.5 cms from end plate D
- D. End plate E. Beryllium copper, silver plated, contact fingers
- F. Pressure sealing cap (in cross section)
- G. Spring and flexible pressure transfer section

Figure 4.1. Temperature-Compensated Brass Resonator.

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the two sections would change temperature (and hence dimensions) at approximately the same rate but during periods of rapid change of temperature the compensating section would exhibit a thermal lag which would tend to nullify the properties of compensation.

Although the experimental tests conducted on the cavity indicated that the effective frequency of resonance of the cavity was essentially unchanged by changes in ambient temperature, the phenomena suggested in the previous paragraph were observed. These are best illustrated by reference to Figure 4.2 and Figure 4.3.

Figure 4.2 illustrates the first three runs during which temperature excursions were held within an upper limit of seventy degrees centigrade. In each of these cases a fairly uniform rise of frequency versus temperature is evident. The same is true in the fourth run but in the fifth and last the upper temperatures were reached rapidly by forced heating. A reverse slope is found in the region of 65-85 degrees. It is believed that this effect was due to the thermal lag of the compensating section.

Some summations of the data applicable to each of the curves is recorded in Table 4.1.

TABLE 4.1

Run Number	Temperature Excursion in °C	Total Frequency Change in Kc	Maximum Frequency Deviation in Kc	Average Instability in ppm/°C.
1	27-65 Rising	3.9	+4.2	0.35
1	67-31 Falling	3.1	+5.3	0.29
2	38-70 Rising	5.0	+5	0.52
2	70-48 Falling	7.6	+8.6	0.79
3	29-67 Rising	2.8	+3.0	0.25
4	27-90 Rising	8.8	+8.8	0.47
5	37-99 Rising	1.6	-5.0	0.07
5	99-40 Falling	3.0	-11.4	0.18

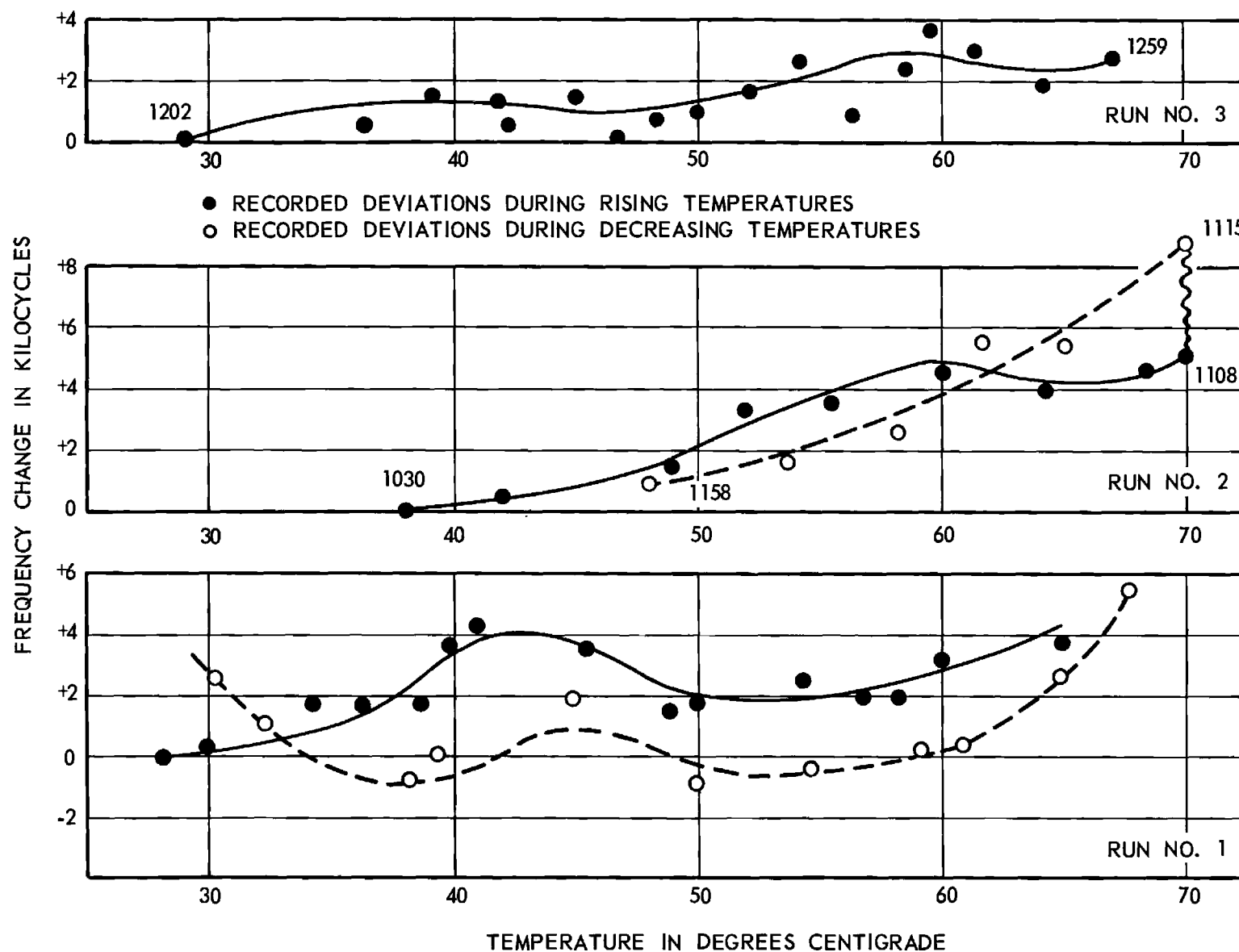


Figure 4.2. Frequency-Temperature Characteristic of a Compensated Brass Cavity (Part One).

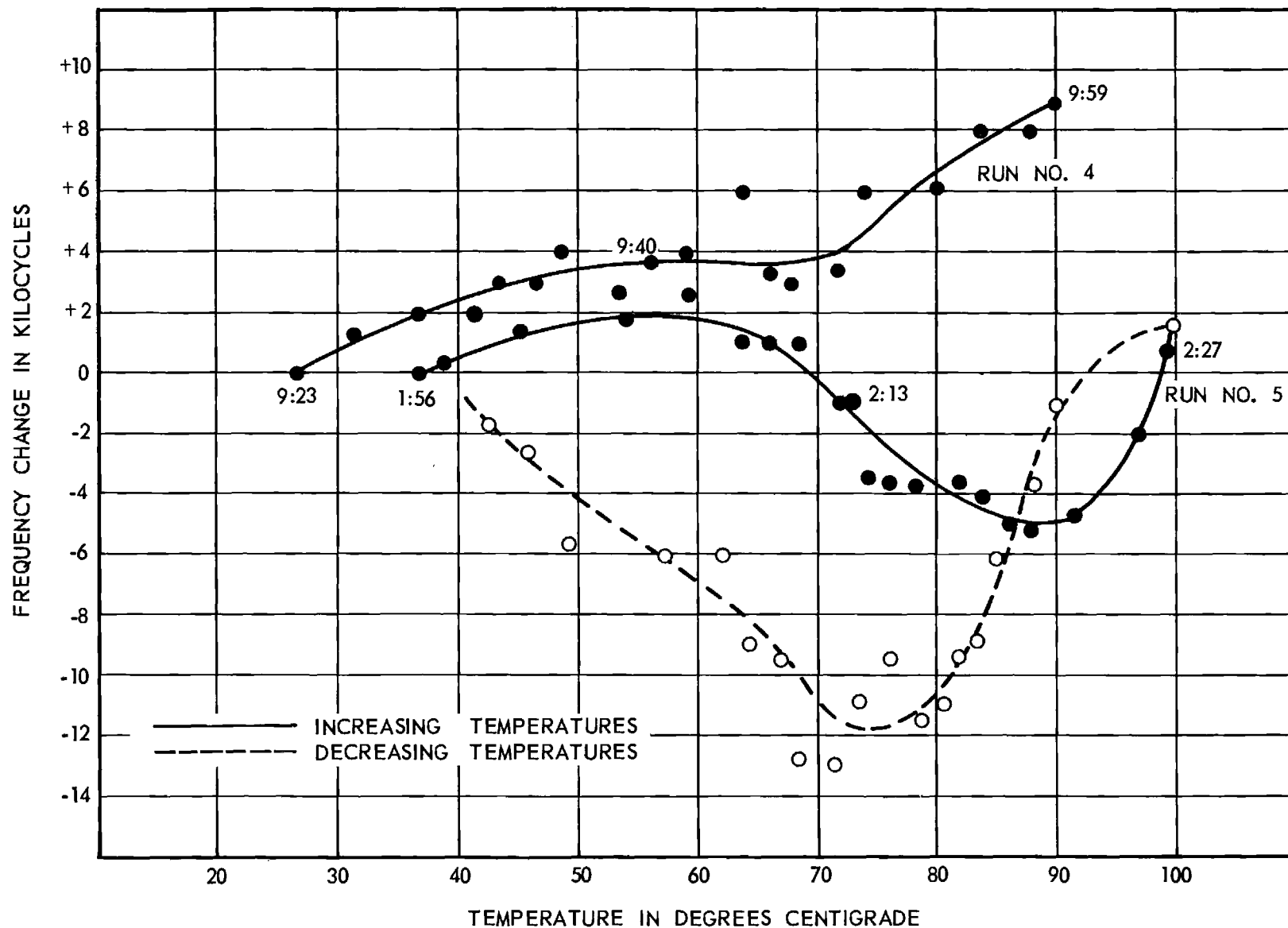


Figure 4.3. Frequency-Temperature Characteristic of a Compensated Brass Cavity (Part Two).

The data for the curves of Figure 4.2 and Figure 4.3 were taken within a ten day period. The cavity was then removed from the test bench and placed upon the shelf to be left untouched for several weeks. Approximately six weeks after the conclusion of the above tests one further run was made to ascertain possible deleterious effects due to storage.

This test has indicated that the temperature compensating properties have not been adversely affected. In a temperature run involving one hour to bring the cavity temperature from 27°C to 100°C a total frequency deviation of 10 kilocycles resulted. The maximum frequency deviation was also 10 kilocycles. The average instability was 0.47 ppm/°C.

The Q of the cavity, however, had suffered. The cavity in its original form was calculated to have a Q of approximately 9500 when evacuated or when filled with dry nitrogen. When this cavity was originally measured on the Cavity Q Meter a Q of 8500 to 9000 was indicated. However, after six weeks storage the Q appeared to have decreased to about 5000. This change is believed to be due to leakage of the cavity, a leakage which permitted entrance of moist air. This mixing of moist air with the dry nitrogen, which originally filled the cavity under conditions of partial vacuum, could and apparently did seriously degrade the Q. Fortunately, the problem of adequate sealing does not appear difficult in the case of a cavity having metal walls and metal end pieces. Hence the leakage in this case is not considered of major significance in evaluation of the capabilities of such a cavity.

In summation, the compensated brass cavity appears to quite adequately solve the problem of temperature instability in the case of an untuned cavity. Whether or not the same principles can be utilized in the case of tunable cavities remains the basis of future investigation. Various possibilities are now under consideration and it is hoped that at least one tunable cavity can be constructed during the period of the present contract.

The cavity discussed above is resonant at about 300 megacycles. Although this frequency is below those frequencies of primary interest to this project it was felt that no generality was lost by operating at this lower frequency. A simple scaling of dimensions should produce

an equivalent resonator at higher frequencies. The choice of the 300 megacycle region permitted use of the Cavity Q Meter in an unmodified condition and expedited completion of the tests conducted. It may be noted here, however, that modifications now being made to the Q Meter will soon permit measurements at much higher frequencies.

Ceramic Resonator

The low coefficient of expansion of Stupalith has indicated that it might serve as a suitable base for resonator construction. During the period of this report two such cavities have been under construction. One is completed, the other is expected to be finished soon. A cross-section of a Stupalith base cavity is shown in Figure 4.4.

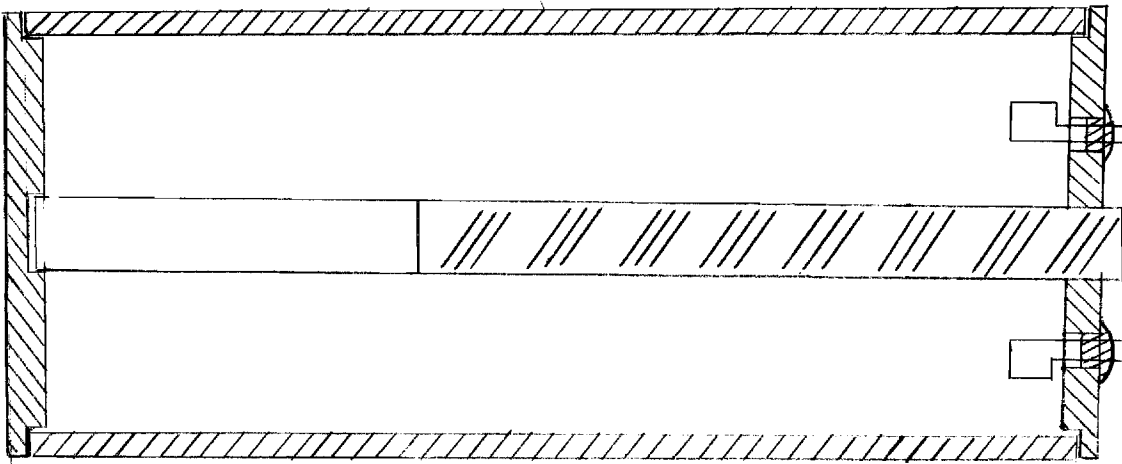


Figure 4.4. Cavity Formed of Stupalith.

The steps involved in fabricating such a resonator are numerous and a number of technical problems have been found to arise. Step-by-step procedures, including problems and precautions, are tabulated here for reference.

1. With coarse emery paper or file remove all rough, uneven or badly discolored spots on the rod and tubing. Experience has shown that such imperfections will not hold a silvered surface.

2. Insure that the ceramic pieces are completely clean. If in doubt scrub thoroughly with water and detergent. Follow this washing by thorough rinsing and by baking in a 300-350° Fahrenheit oven for at least one hour to remove all traces of moisture which may have been absorbed.

3. Spray the inside surface of the tubing, the end-plates, and desired portion of the rod with a silver-based paint such as Du Pont number 4760 silver paste ⁽³⁾. Use sufficient thinner (Toluol) to insure a spray which will thoroughly wet the surface. Failure to use a wetting spray will result in peeling of the silvered surface. The outside of the tubing need not be sprayed unless so desired but if not the tubing must be thoroughly covered with some sealing agent such as Glyptal (after oven-firing is completed).

4. Fire in oven at 1250-1350°F. Remove, cool, and buff until smooth silver surface is in evidence. Then test with ohmmeter probes to seek out any spots where lack of conductivity indicates failure of silver adhesion. Spray or paint all such spots and fire again. Complete sealing of all points on the surface of the ceramic is very important. Otherwise the porous ceramic will soak up quantities of electroplating liquid during the plating process. This liquid, under heat, will produce bubbles in the silvered surface.

5. Carefully seal all parts not electrically active and not having fired-silver coating with a sealing compound such as Glyptal.

6. Electroplate to add a layer of silver at least one thousandth inch thick on the tubing and slightly deeper on the rod and end plates. Remove from bath, thoroughly rinse free of cyanide solution, air-dry, and polish.

7. A final oven firing at a low temperature is now desirable. Temperatures of 250-300°F will drive out vestiges of moisture entrapped in the porous ceramic. This firing should last for a 3 to 4 hour period. The ceramic must be brought up to temperature slowly or bubbles may occur. Under slow heating the vestigial gases appear to filter through the silver coatings without injuring it.

8. The various pieces may now be soldered together. The recommended procedure is to tin all abutting surfaces with 40-60 solder, then to assemble the whole resonator with end pieces clamped in position and to use an oven to bring the whole assembly up to the melting point of solder. Care must be exercised that the temperature does not exceed the necessary minimum. At higher temperatures the molten solder will often loosen the silver from its ceramic base.

Some doubt exists as to the ability of solder to maintain a seal between the silvered ceramic components in case a marked change of ambient temperature occurs. Solder has a temperature coefficient of expansion of greater than twenty and considerable relative movement of a large bonding surface might be presumed to occur. However, no evidence of failure of bonding has been evidenced to date. It is believed that the thin films of solder utilized may suffer distortion rather than fracture during expansion and hence preserve the resonator's sealed properties.

V. CAVITY CONTROLLED OSCILLATORS

Introduction

Oscillators which were designed to operate in the 300 megacycle region and which utilized a coaxial cavity as a frequency determining element were discussed in detail in an earlier report. (4) These oscillators were so configured that the tubes and associated elements were separated from the cavity by means of coaxial cables. This arrangement was for the precise purpose of permitting examination of the temperature characteristics of the cavity while the remainder of the circuit remained at constant temperature.

These oscillators utilized a circuit arrangement in which the tube served as a grounded-grid amplifier and the cavity formed a link in the positive feedback loop from plate to cathode. In this configuration the requirement of zero phase between plate and cathode (true at low frequencies) may be thought of as occurring if the cavity introduces no phase shift. If this is true, then a shift of resonant frequency of the cavity may be reflected almost directly as an approximately equal change in the frequency of oscillation of the complete system. This situation of one-to-one frequency dependency appears to be not necessarily the case when the cavity serves as a reactive element rather than as a transfer device in the feedback loop.

The recent development and utilization on this project of the Cavity Q Meter has permitted passive measurements of coaxial cavities. The relative simplicity of measurements by this means as well as the quite complete isolation of the cavity makes it appear neither necessary nor desirable to make the cavity a part of an oscillatory system if one desires only to determine the characteristics of the cavity. The problem of establishing the factors which contribute to overall oscillator performance can be separated into two distinct steps if the frequency determining component can be measured under passive conditions. The first of these is determination of the temperature stability and the Q of the cavity. This can be achieved, as already noted, by use of the Cavity Q Meter. The second step may be

carried out at constant temperature. In this step the effects upon the oscillator of changes in plate voltage, of loading, of changes of coupling, etc., may be studied. The results of the two steps can then be combined in a prediction of overall performance.

The type of oscillatory circuit mentioned in the first paragraph used a grounded-grid amplifier, coaxial cables, and utilized the cavity as a transfer device. This oscillator was shown to exhibit excellent stability but it was, unfortunately, rather critical with respect to adjustments. In view of this fact, and also in light of the quite adequate treatment accorded it in the earlier report, attention has now been directed toward a circuit arrangement in which the cavity acts as a reactive element. Preliminary investigations have indicated that some advantages accrue from choice of this configuration, particularly when the oscillator is coupled directly into the cavity. Incomplete experimental data indicate that initial adjustment is simplified and that the stability of the oscillator may be potentially quite good. On the other hand, if the oscillator is coupled into the cavity by any transmission line, however short, it appears that stable oscillations are more difficult to obtain and that the stability is much more critical to variation of circuit parameters.

In the succeeding paragraphs the basic oscillator is described, some comments relative to stability are advanced, and the results of experimental tests are summarized.

The Basic Circuit

At the frequencies of interest simplicity of circuitry is desirable in order to minimize effects of the multiple feedback paths existing in complex circuits. The only arrangement which is known to have been used above 500 megacycles, utilizing conventional tubes, has been operated by Loofburrow and Morris ⁽⁵⁾ as a tool for determination of limitations of the 6AF4 triode. The circuit has not, as far as known, been investigated to determine its feasibility as a stable frequency source. Figure 5.1 shows the circuit as originally configured.

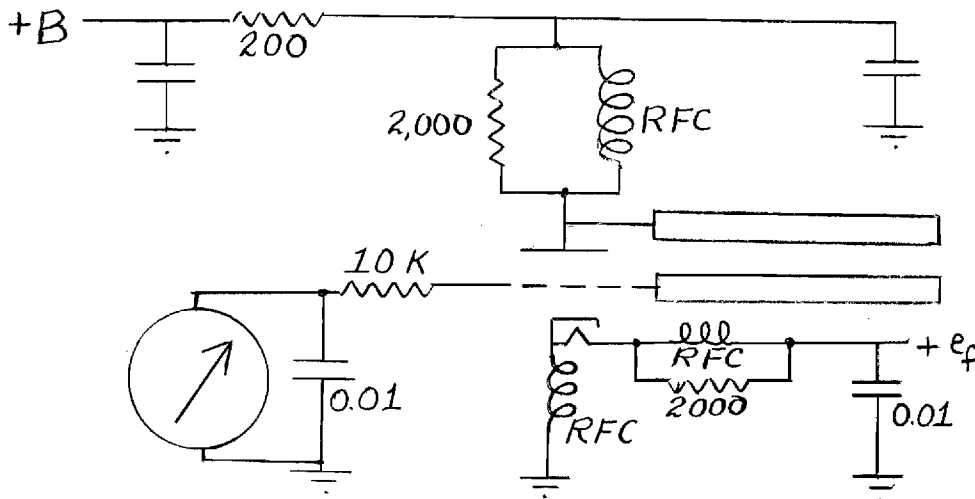


Figure 5.1. Oscillator Circuit for 500-900 Megacycle Range.

The transmission line of plate and grid may, of course, be open or closed. In the latter case a coupling capacitor separates the plate line (and grid) from the d-c voltage at the plate. The original investigators have indicated that frequencies approaching 800 megacycles can be achieved using a closed line. Experimental work on this project indicates that at frequencies above 600 megacycles oscillator action is more satisfactory, from several standpoints, if an open line is used. Summaries of experimental data listed in later pages of this section will amplify this statement.

This circuit represents a form of Colpitt's oscillator. The plate to grid line must be inductive in order to resonate the stray and interelectrode capacitances. If this line is now inserted in a cavity under conditions wherein the cavity is strongly excited at or near its resonant frequency it may be assumed that the loop loses its identity as such and that the loop-coupled cavity now represents the inductance formerly supplied by the loop alone.

An equivalent circuit applicable to the frequency range under consideration (500-900 Mcs.) is shown in Figure 5.2.

The lead inductances (L_k, L_p, L_g) form an appreciable portion of the total inductance between plate and grid. They are, of course, internal to the tube pins which form external connections to the plate and grid.

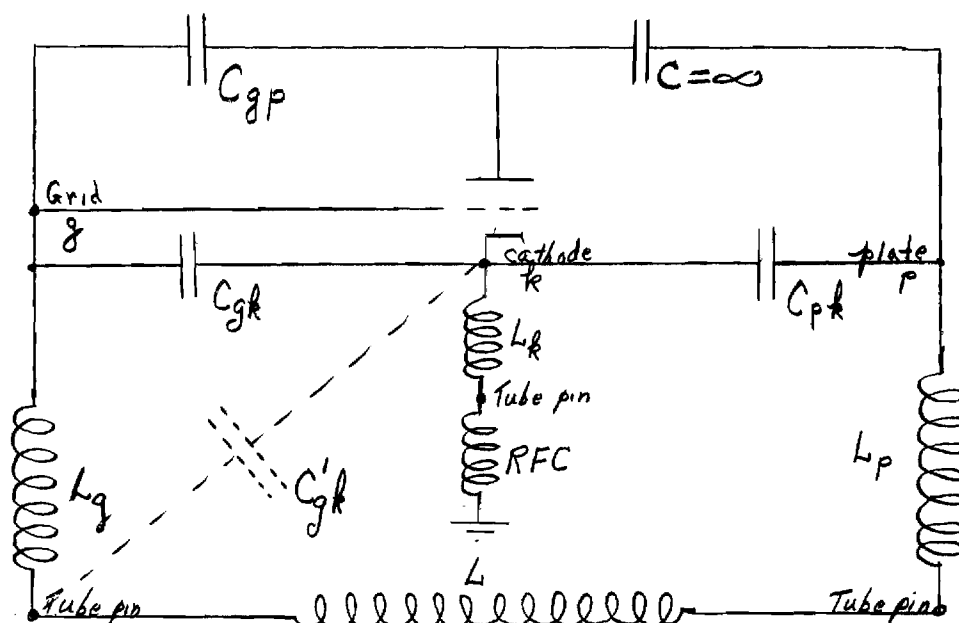


Figure 5.2 Equivalent Circuit Applicable at UHF.

Fortunately, in the absence of a padding condenser (illustrated by dotted line of C'_{gk} in Figure 5.2), these internal inductances add to the external inductance of the transmission line. Hence the three inductances may be lumped for convenience of analysis into one equivalent inductance.

Experimental Cavity-Controlled Oscillator

It was realized that if considerable significant data on a specific oscillator was to be obtained provisions must be made for rapid connections to, and disconnections from, the cavity. The first method proposed was to couple the oscillator to the cavity by a length of transmission line. This approach was attempted but all factors concerned, the length of line, the size of coupling loop, etc., were found to be so critical that the arrangement was considered to be completely unsatisfactory. The next step was to reduce the length of line to a minimum by placing the oscillator (tube) chassis close to the emergent loop of the cavity. With this arrangement the transmission line was reduced to two open pieces of wire whose individual length did not exceed one-and-one-half inches. This arrangement proved to be much more satisfactory than did the longer coaxial cable and fairly satisfactory cavity controlled oscillations

were obtained. However, the arrangement was obviously unsound from a mechanical viewpoint and was temporarily, at least, discarded as impractical.

The arrangement which has proved quite satisfactory from all stand points will now be described. A cavity, designed to be resonant at 500 Mc., was constructed utilizing a brass outer cylinder eight inches in length and with an inner diameter of nearly three inches. A silver plated end piece and silver plated tubing center conductor complete the coaxial cavity.

The oscillator conforms to the configuration shown in Figure 5.1. It was built, as shown in Figures 5.3 (a, b,), on a plate which is large enough to support the base and power leads but small enough to fit in a recess grooved into the end piece of the resonator. Figure 5.4a illustrates the complete oscillator. All portions of the oscillator, with the exception of the tube and power leads, fit within the cavity proper. The dimensions of the oscillator may be ascertained by comparison with the type 6AF4 miniature tube or by noting that in Figure 5.3a the oscillator elements occupy a space about one inch long and of a diameter approximately equal to that of the base of the tube.

It will be noted in Figure 5.4b that the plate mounting the oscillator is secured to the cavity by a number of machine screws. These assure a rigid mounting but permit assembly or disassembly in a matter of seconds. With this arrangement the oscillator may be withdrawn from the cavity, tuned externally, and reinserted for testing within a very brief period of time. This fact permitted a moderately rapid accumulation of data.

There being little data available on the performance characteristics of this type of oscillator in the U-H-F range, it was decided to first accumulate some experimental data on the oscillator proper prior to investigating the effect of the cavity upon its performance. The first configuration studied was identical to that of Figure 5.3 but the length of the grid-plate loop was varied during the tests.

The first series of tests investigated the stability of the oscillator alone under various conditions of loading. For convenience,

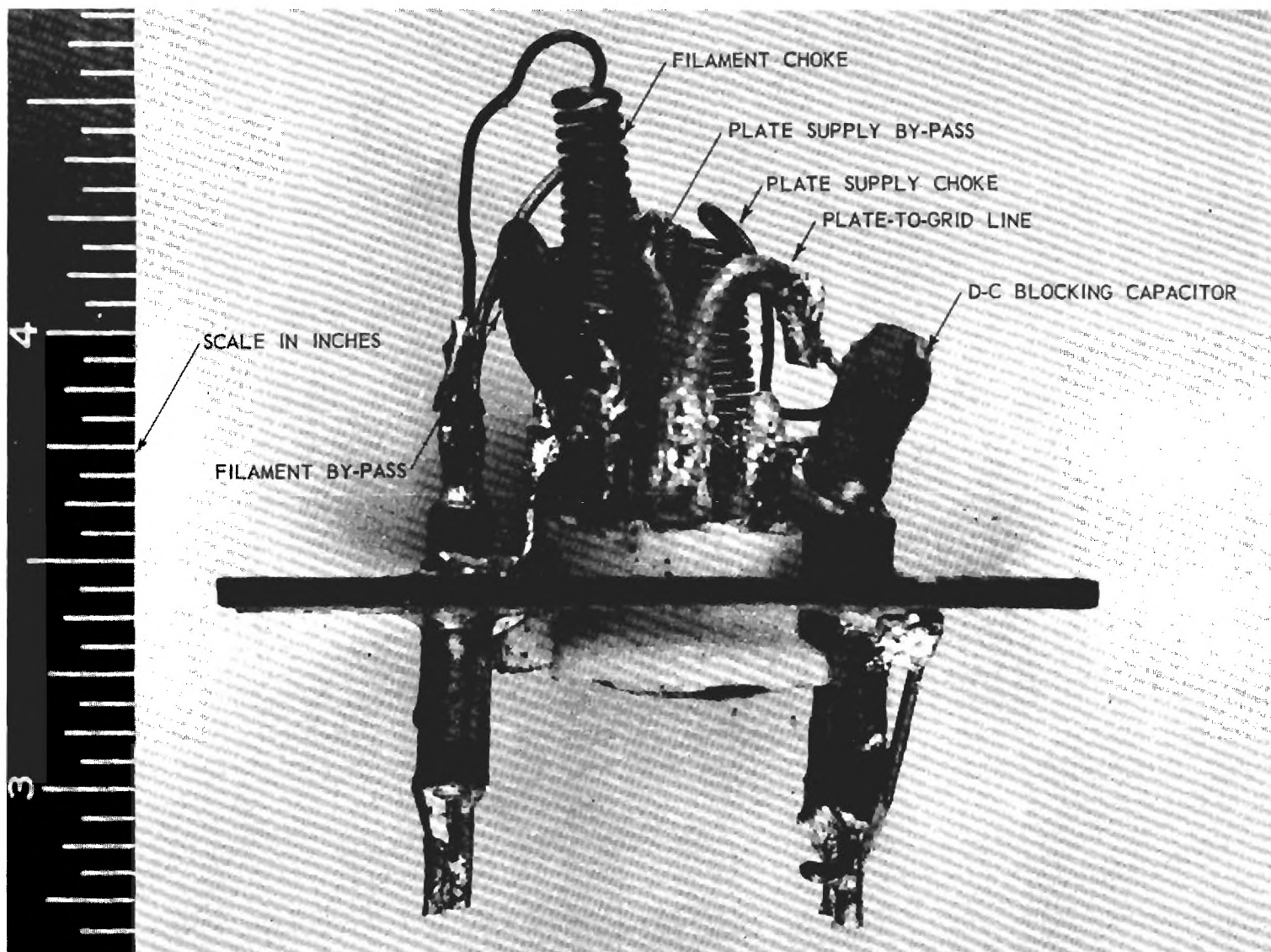


Figure 5.3a. View of 500 Mc. Oscillator.

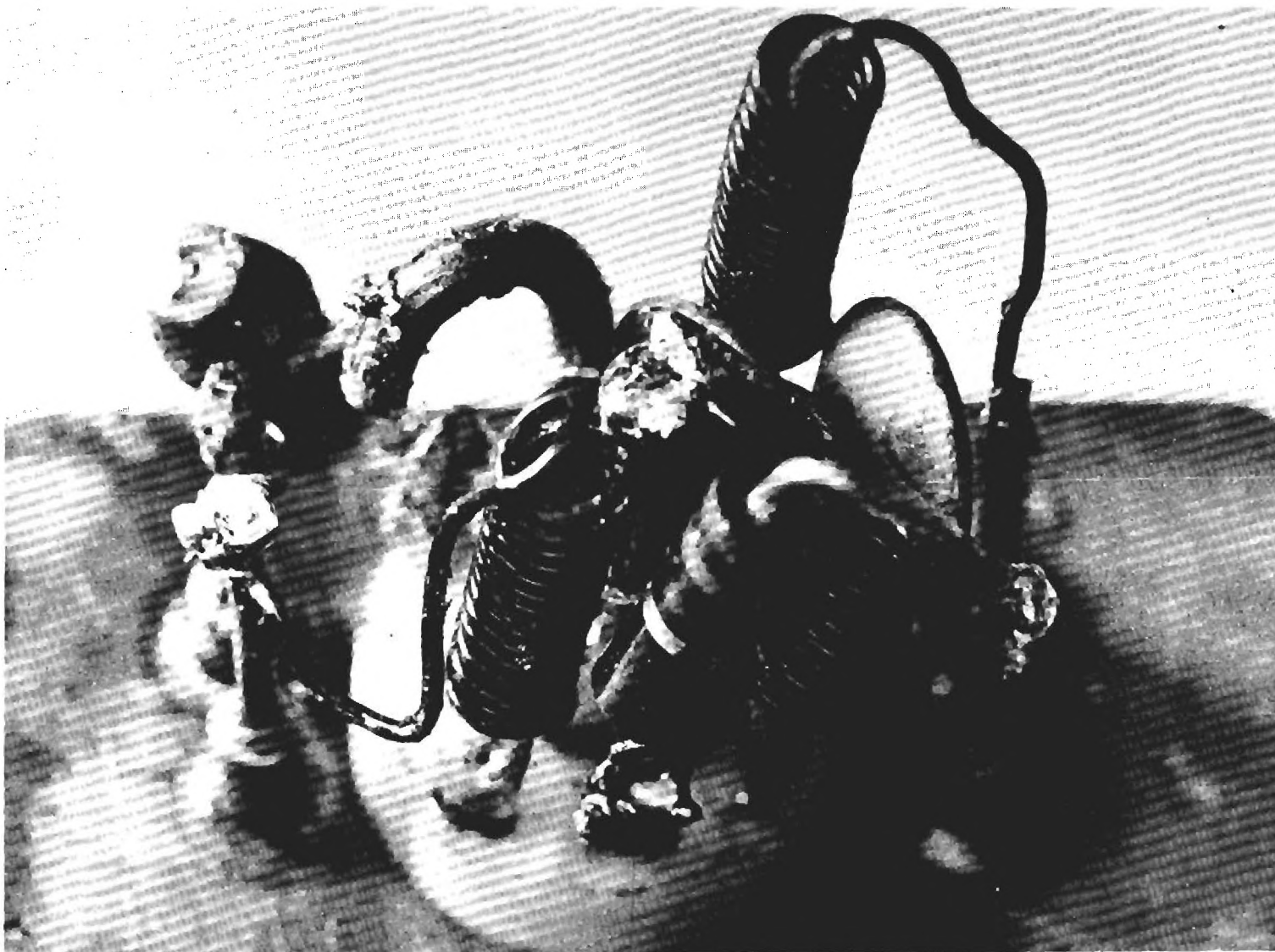


Figure 5.3b. View of 500 Mc. Oscillator.

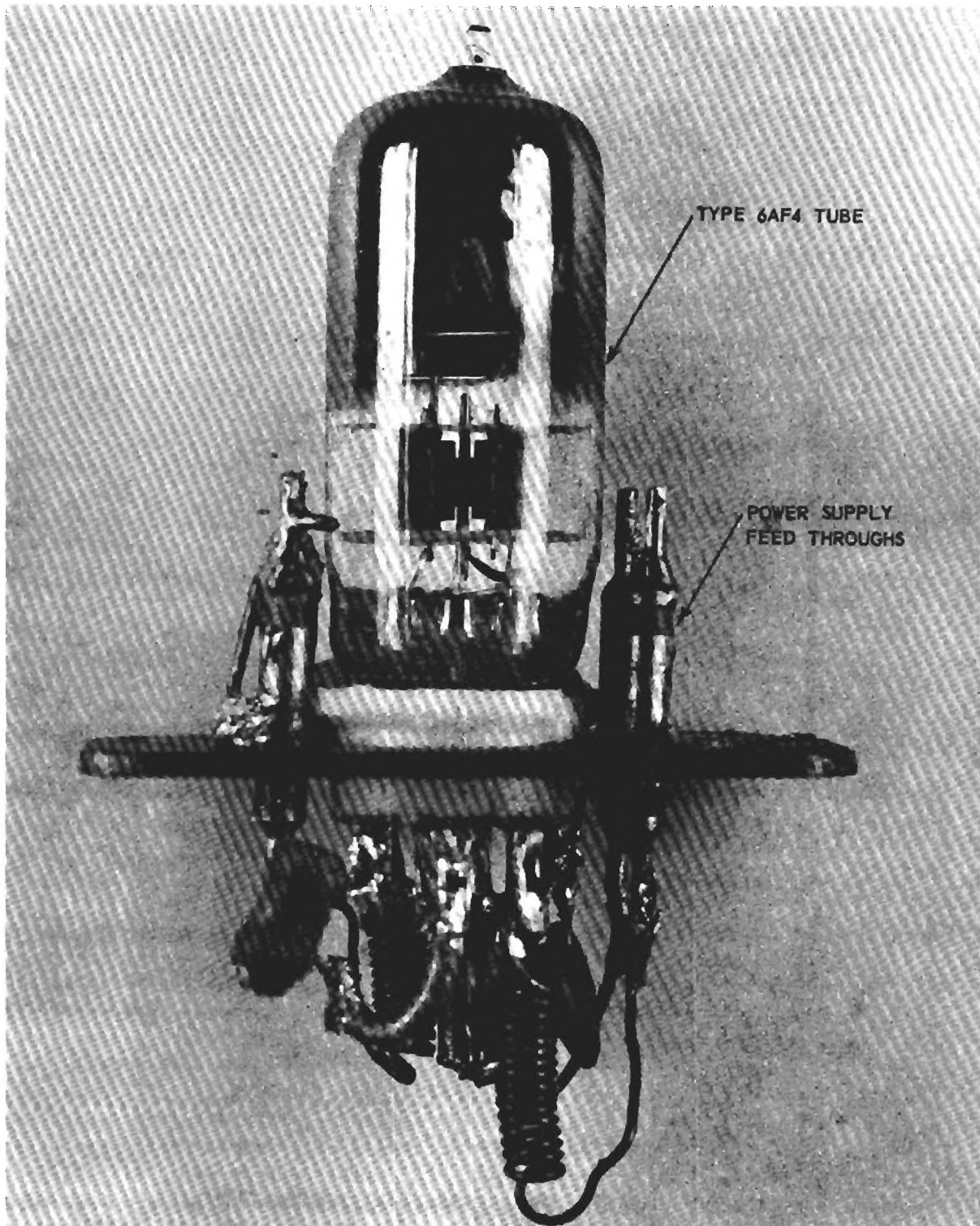


Figure 5.4a. View of Assembled 500 Mc. Oscillator.

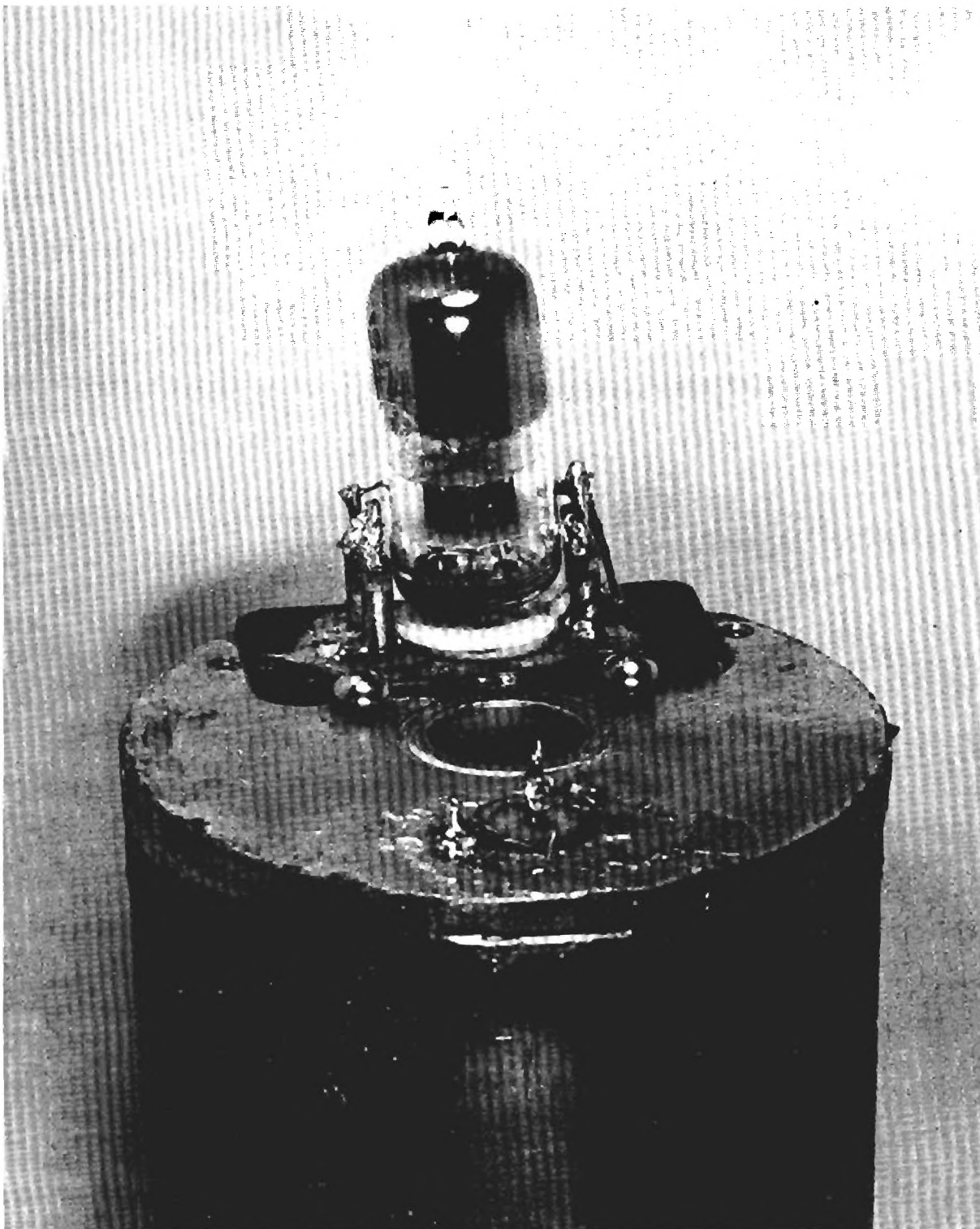


Figure 5.4b. View of Assembled 500 Mc. Oscillator.

loading was effected by placing conductive loads between grid and ground. During this test the plate-to-grid line consisted of a closed loop approximately three-fourths of an inch in length. The changes in frequency resulting from changes in plate voltage were recorded and are plotted in Figure 5.5. The nominal frequency during this series was about 475 Mc.

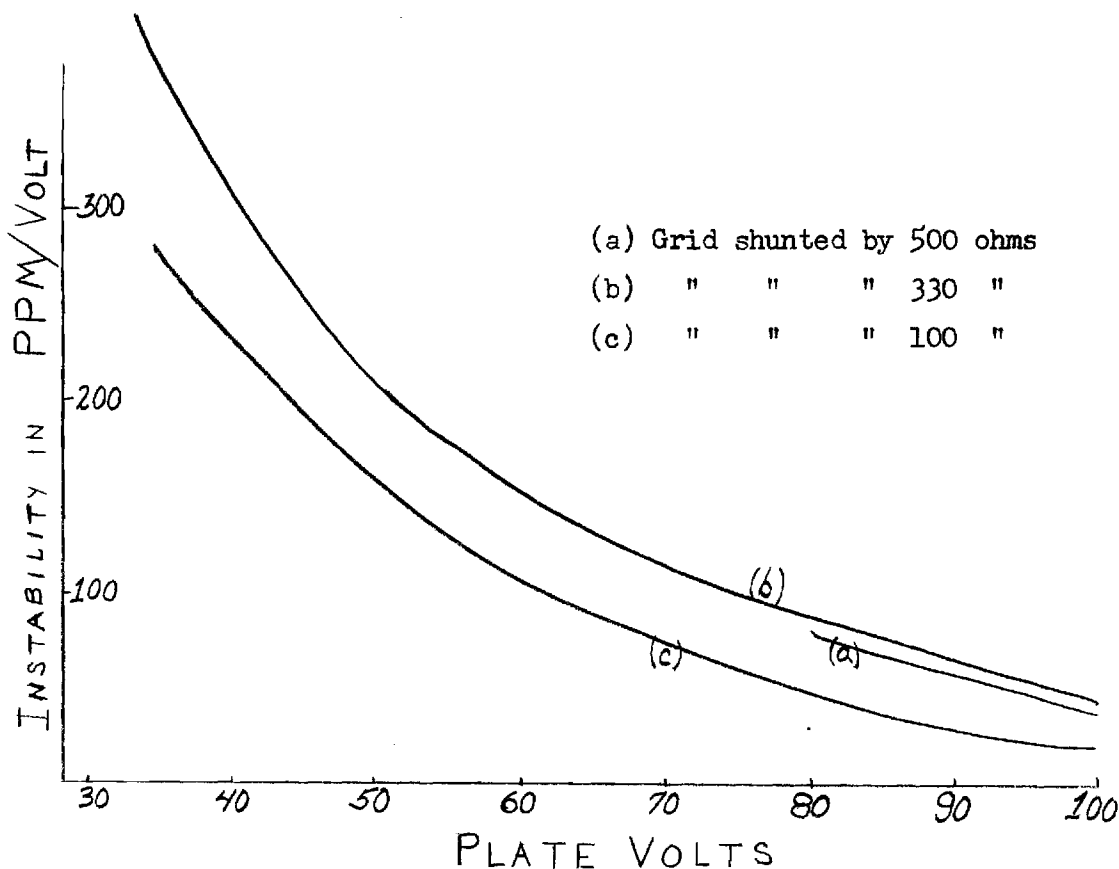


Figure 5.5. Plate Voltage Effects in an Unstabilized Oscillator.

It will be noted that the stability was very poor, being at its best about 20 ppm/volt and at its worst being several hundred parts. It is of interest, although of no immediate significance, to note effects of certain changes in parameters. A few are listed:

- a. Loop made $2\frac{1}{2}$ " long. Frequency: 202 Mc, Instability: 30 ppm/volt.
- b. Same as (a) but 3 uuf added, plate-to-ground. Frequency: 188 Mc. Instability: 28 ppm/volt.

- c. Same as (a) but 3 uuf added, grid-to-ground.
Frequency: 200 Mc. Instability: 23 ppm/volt.
- d. Same as (a) but 15 uuf added, plate-to-ground.
Frequency: 165 Mc. Instability: 85 ppm/volt.

Efforts were now made to bring the oscillator under control of the cavity. In early tests results were negative, the oscillator running vigorously at frequencies above or below the frequency of cavity resonance at 491 megacycles but refusing to run at or near this frequency. Inasmuch as action of this type was suggestive of possible overcoupling, a careful survey of the configuration was made. Now it may be seen from Figure 5.4b that the plate-grid loop of the oscillator, a loop which serves both as an inductive feedback path and as a means of coupling to the cavity, is inserted into the end of the coaxial cavity. A cross-sectional view of this coupling is shown in Figure 5.6. A loop in this position has been shown ⁽⁶⁾ to have a coupling coefficient of a value as given in equation 5.1 below, when the loop is oriented so as to have its plane perpendicular to the lines of magnetic flux existing in the energized cavity resonator.

$$\frac{M^2}{L_a} = 1.19 \times 10^{-8} \frac{A^2}{r^2 \ell (r/\ell)^2 + 1.49} \quad \text{henries} \quad (5.1)$$

where (in MKS rationalized units)

A = area of loop

r = distance of center of loop from axis of resonator

ℓ = length of center conductor

M = mutual inductance between loop and cavity

L_a = equivalent inductance of cavity

The initial position of the loop, for the oscillator under discussion, was at a point quite close to the inner conductor of the cavity. The plane of the loop, in addition, lay along a radial line, i.e., in a position perpendicular to the lines of magnetic flux in a cavity which is excited in the dominant or TEM mode. In this position a relatively high coefficient of coupling existed. The steps taken to

reduce the coupling consisted of rotating the whole oscillator assembly to place the loop near the outer conductor and of rotating the loop about its own axis through approximately 45° . An estimated reduction of coupling coefficient of about 6:1 resulted.

This relatively simple procedure is emphasized because in the case of the small loop these steps were all that were required to bring about satisfactory oscillator-to-cavity coupling.

Before listing the results of experimental tests it is desirable to give consideration to the equivalent circuit of the loop-coupled cavity. Beringer has shown ⁽⁷⁾ that in the neighborhood of a specific resonance that the loop-coupled cavity may be represented as shown in Figure 5.6a or 5.6b.

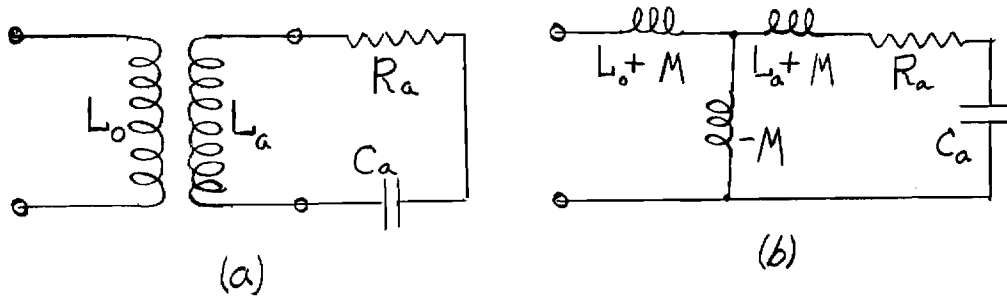


Figure 5.6. Loop Coupled Cavity in the Vicinity of Resonance.

L_o = self-inductance of loop

L_a , R_a , C_a = self-inductance, capacitance, and losses of cavity at frequency of maximum impedance

The circuit has an input impedance of

$$Z_a = j\omega L_o + \frac{\omega^2 M^2}{j\omega L_a + R_a - j\frac{1}{\omega C_a}} \quad (5.2)$$

or,

$$Z_a = j\omega L_o + \frac{j\omega^3 M^2}{L_a (\omega_a^2 - \omega^2 + j\frac{R_a \omega}{L_a})} \quad (5.3)$$

where

$$\omega_a^2 = \frac{1}{L_a C_a}.$$

If Q_a is defined as

$$Q_a = \frac{\omega_a L_a}{R_a}$$

$$Z_a = j\omega L_o + \frac{\frac{j\omega^3 M^2}{L_a}}{\omega_a^2 - \omega^2 + \frac{j\omega \omega_a}{Q_a}}. \quad (5.4)$$

After some simplification, dropping terms which are negligible in the case of high Q 's, we have

$$Z_a = j\omega L_o - j\omega \frac{M^2}{L_a} + \frac{j\omega \omega_a^2 \frac{M^2}{L_a}}{\omega_a^2 - \omega^2 + \frac{j\omega \omega_a}{Q_a}}. \quad (5.5)$$

If the last term in 5.5 is rationalized there appears a reactive term whose denominator is always positive and whose numerator contains the product $+ j\omega \omega_a^2 (\omega_a^2 - \omega^2)$. This is positive for $\omega_a > \omega$ and negative for $\omega_a < \omega$. From the standpoint of the oscillator, it signifies that the inductance of the loop L_o is reduced, near cavity resonance, by a fixed term M^2/L_a and is increased or decreased by the remaining factor depending upon whether or not the frequency of oscillation is above or below the resonant frequency of the cavity.

The situation wherein the oscillator may operate at a frequency either above or below that of resonance of the cavity is at variance with the situation existing in crystal oscillators of a comparable type (Pierce) wherein the resonator must always exhibit reactance if oscillations are to occur. The difference of action is, of course, due to the fact that inductive reactance exists in the absence of cavity excitation and the cavity exercises its control by a change of

the basic inductance.

The arguments brought above are from classical theory, it remains to show their relationships in practical circuits. The oscillator illustrated in Figure 5.4a-b has served as a test vehicle and data accumulated by its use, although still limited, tends to support the theory.

As a first step in experimental analysis, careful measurements were made of the response curve of the cavity. The arrangement utilized for measurement purposes is illustrated in Figure 5.6.

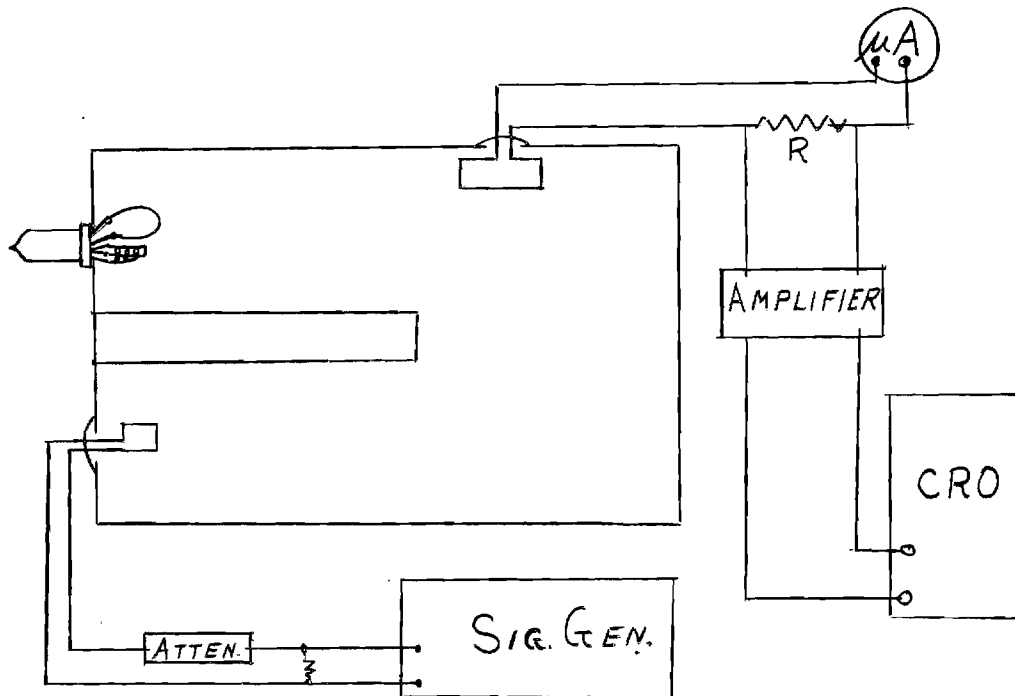


Figure 5.6. Arrangement for Measurement of Cavity Response.

Every attempt was made to maintain conditions identical to those which existed during oscillations. The oscillator (tube and loop) remained in the cavity in normal position as illustrated in Figure 5.6. Its filaments were energized and a low d-c voltage was applied to the plate. In this manner the tube and its components may be presumed to present impedance negligibly different from that when in the active state. Other parts of the system were similarly

treated. The coupling loop at the lower left hand end of the cavity in Figure 5.6 was open-circuited when the oscillator was self-activated; during this test an essentially equivalent condition was effected by thorough decoupling of the signal generator. The output loop, shown at the top and right in the figure, heavily loads the cavity when actual oscillations existed. However, it did so identically during the test. This assumes that the oscilloscope presents an infinite impedance to the modulation frequency (400 cps) of the testing generator.

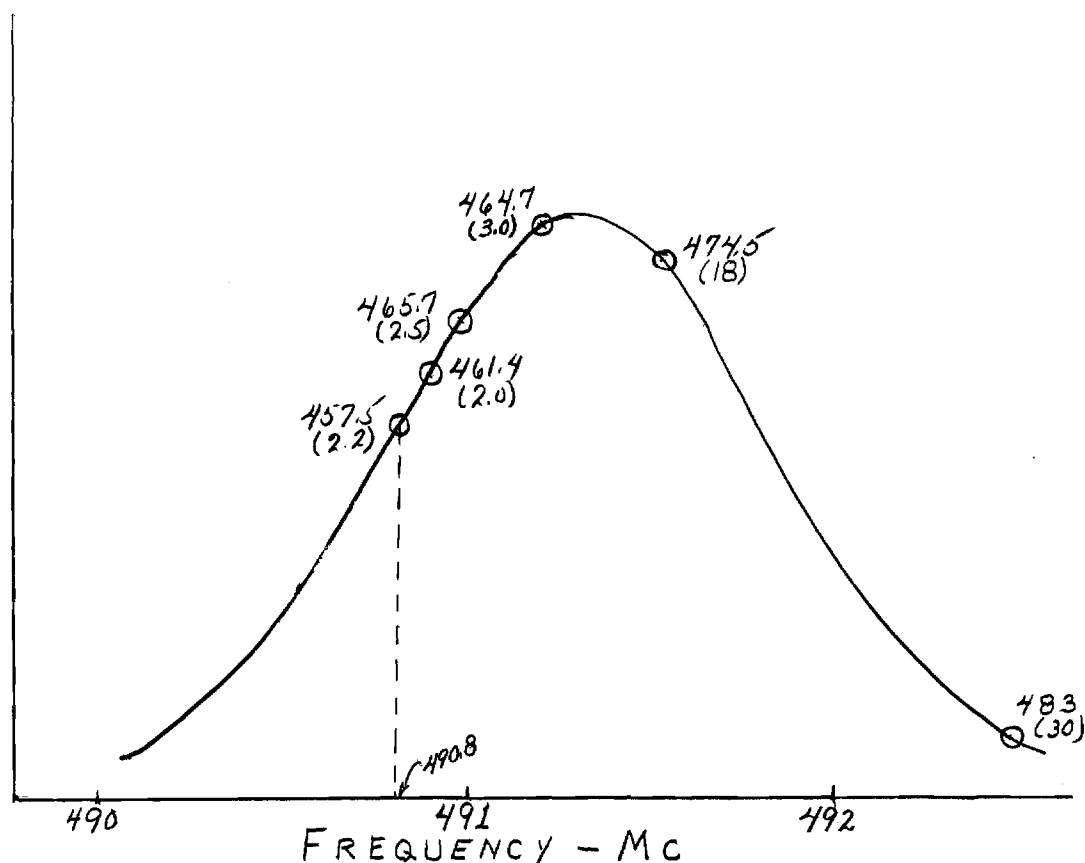


Figure 5.7. Response Curve of Cavity and Oscillating Frequencies.

A plot of the response of the cavity under these loaded conditions is shown in Figure 5.7. Superimposed upon the curve are a series of points. Each point represents one test in which the oscillator was operated under cavity control. The frequency in each case may be determined from the abscissa of the point. For example, the point farthest to the left applies to a cavity controlled oscillation of 490.80 Mc.

The two figures beside that point represent respectively, the free-running frequency (that existing when withdrawn from the cavity), and the instability in parts per million per volt (ppm/volt). The point given as an example shows that the oscillator which operated in the cavity at 490.80 Mc. had an instability of 2.2 ppm/volt and that when withdrawn from the cavity that it ran at a frequency of 457.5 Mc. As illustrated in Figure 5.5 its instability outside the cavity was probably somewhere between 20 and 50 ppm/volt.

It will be noted in Figure 5.7 that the frequency of cavity-controlled oscillation followed a sequence determined by the free-running frequencies. That is, a higher free-running frequency was matched by a higher cavity-controlled frequency. This effect is predicted by equation 5.5. It will also be noted that the region of stable oscillation is restricted to a small portion of the response curve. The step-by-step effects of voltage variation are shown in Figure 5.8. The conditions correspond, in most cases, to the frequencies shown in Figure 5.7. Some considerations of stability are given in a later part of this section, and different results obtained when another type of plate-to-grid loop was utilized are listed in the succeeding paragraphs.

One further item needs to be added to the data accumulated on the above oscillator for the configuration described. This item relates input impedance and r-f excitation. These data were obtained by modifying the arrangement of Figure 5.6 by adding a radio-frequency bridge at the input terminals. The impedance at this point was measured and has been plotted in Figure 5.9. A copy of the curve of Figure 5.7 has been superimposed upon Figure 5.9. It will be noted that points of stable operation shown in Figure 5.7 occur at frequencies at which the rate of change of reactance is large. It will also be noted that a rapid rate of change of reactance occurs even though the impedance levels are low. The combination of low impedance levels and rapid reactance change is generally accepted as a condition tending to promote stability in oscillators.

After conclusion of tests using a closed line in the plate-grid circuit the oscillator was revised. By use of various line configurations it is hoped to establish the effect of various types of

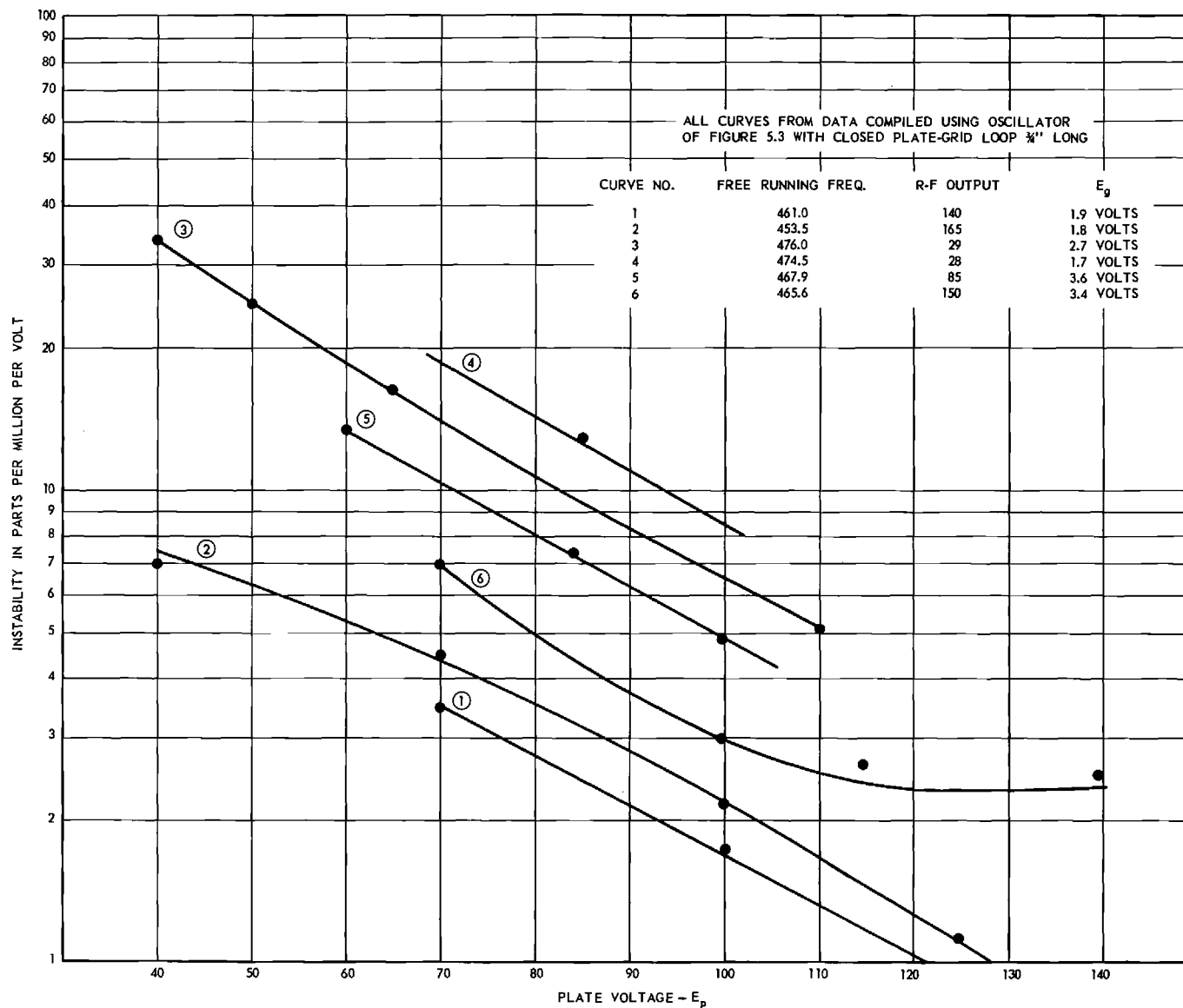


Figure 5.8. Instability of Oscillator as Function of Plate Voltage.

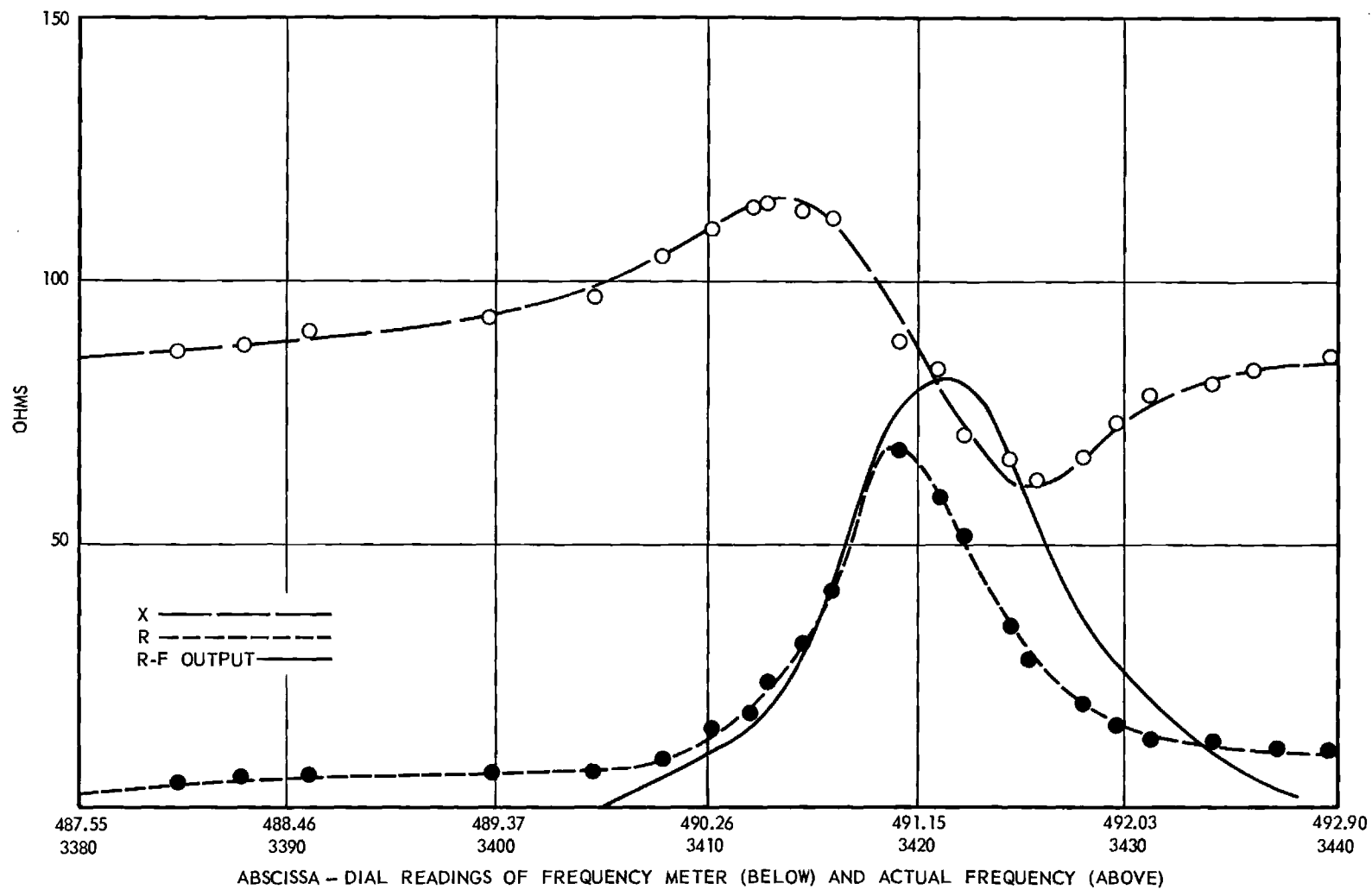


Figure 5.9. Input Impedance of Loop-Coupled Cavity.

coupling loops upon oscillator performance. The closed 3/4" plate-to-grid loop was replaced by an open line two inches long but with the addition of a 3-12 mmf capacitor as a termination. The results of a series of tests conducted on this oscillator are summarized in Table 5.1. The instability results were obtained in this case by changing the plate voltage in large steps. The average instability in each range is shown.

It will be noted that the characteristics of the oscillator using the capacitor terminated open line appear much superior to those existing in the presence of a shorter closed line. The precise reason for this situation is undergoing study and will be reported upon at the conclusion of further analytical and experimental study.

TABLE 5.1.

Frequency (Mc)		Cavity-Controlled	Instability
Outside Cavity	In Cavity	75-150 Volts	125-150 Volts
472.9	491.59	1.9 ppm/volt	0.7 ppm/volt
463.6	491.33	2.2 "	1.4 "
459.8	491.25	1.9 "	0.7 "
456.4	490.86	2.2 "	1.4 "
453.3	490.80	2.3 "	1.4 "
448.5	490.60	1.9 "	0.7 "

Stability Considerations

The factors controlling the stability of an oscillator of the type under discussion are so many and varied that it is doubtful that any complete analytic formulation may be effected which can closely predict the stability of a particular configuration. This is particularly true at those frequencies where lead length inductances play a major part in determination of frequency. This situation is illustrated in Figure 5.2 where C'_{gk} represented a physical shunting capacitance. The fact that the network seen looking into the grid pin becomes a pi of inductance and capacitance immeasurably complicates analysis.

It appears, however, that certain generalities, at least, may be drawn from the circuit. It is convenient to begin an analysis by placing the circuit of Figure 5.2 in a more convenient configuration. The modified form is shown in Figure 5.10. In this circuit L' represents the sum of L , the inductances exterior to the tube pins, and of the total lead length inductances of plate and grid measured from tube pin to electrode in each case.

The circuit is broken as indicated to permit an analysis of the type suggested by Heising ⁽⁸⁾. The impedances seen looking into the two sections are Z_1 and Z_2 , where

$$Z_1 = R_1 + jX, \quad Z_2 = R_2 + jX_2$$

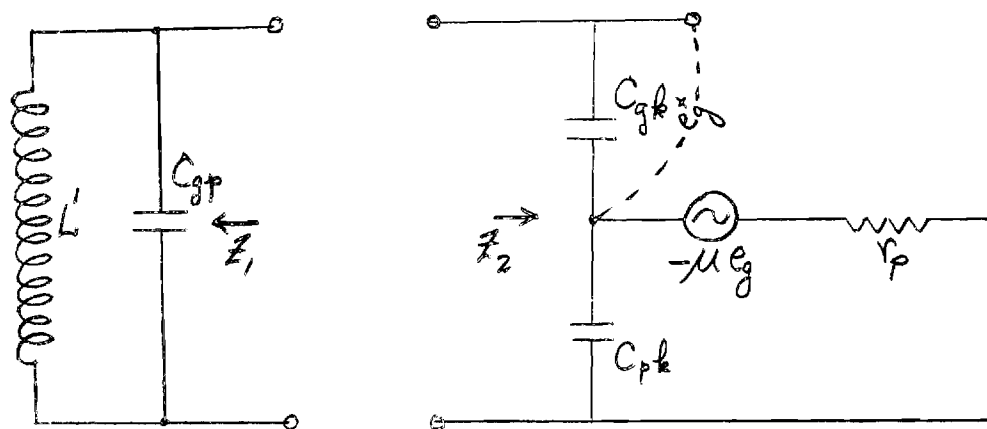


Figure 5.10. Equivalent Circuit in Form for Analysis.

Now a necessary condition for oscillation is

$$X_1 + X_2 = 0 \quad (5.6)$$

Also

$$\begin{aligned} X_1 &= X(f, E) \\ X_2 &= X(f, E, u, r_p) \end{aligned}$$

where

u, r_p = tube parameters as normally designated

E = d-c plate voltage.

Now it is also true from equation 5.6 that

$$dX_1 + dX_2 = 0. \quad (5.7)$$

If equation 5.7 is expanded by the rule of the complete derivative, one obtains

$$\frac{\partial X_1}{\partial f} df + \frac{\partial X_1}{\partial E} dE + \frac{\partial X_2}{\partial f} df + \frac{\partial X_2}{\partial E} dE + \frac{\partial X_2}{\partial u} du + \frac{\partial X_2}{\partial r_p} dr_p = 0. \quad (5.8)$$

If equation 5.8 is solved for df/dE one obtains

$$\frac{df}{dE} = - \frac{\frac{\partial X_2}{\partial u} \cdot \frac{du}{dE} + \frac{\partial X_2}{\partial r_p} \cdot \frac{dr_p}{dE} + \frac{\partial X_1}{\partial E} + \frac{\partial X_2}{\partial E}}{\frac{\partial X_1}{\partial f} + \frac{\partial X_2}{\partial f}}. \quad (5.9)$$

It may be presumed that significant changes in interelectrode capacitances occur when the plate voltage (and current) undergo change. Experimental data on and theoretical considerations of such capacitance changes are available. ⁽¹⁰⁾ It has also been pointed out by another author ⁽¹¹⁾ that C_{gk} and C_{pk} are of fundamental interest in a Colpitt's type oscillator and that C_{gk} undergoes a capacitance change many times greater than C_{pk} . In this case, then, we can disregard a change in C_{pk} and write

$$\frac{\partial X_1}{\partial E} \approx \frac{\partial X_1}{\partial C_{gk}} \cdot \frac{\partial C_{gk}}{\partial E} \quad (5.10)$$

and

$$\frac{\partial X_2}{\partial E} \approx \frac{\partial X_2}{\partial C_{gp}} \cdot \frac{\partial C_{gp}}{\partial E}. \quad (5.11)$$

With these substitutions equation 5.9 becomes

$$\frac{df}{dE} = - \frac{\frac{\partial X_2}{\partial u} \cdot \frac{du}{dE} + \frac{\partial X_2}{\partial r_p} \cdot \frac{dr_p}{dE} + \frac{\partial X_1}{\partial C_{gk}} \cdot \frac{\partial C_{gk}}{\partial E} + \frac{\partial X_2}{\partial C_{gp}} \cdot \frac{\partial C_{gp}}{\partial E}}{\frac{\partial X_1}{\partial f} + \frac{\partial X_2}{\partial f}} \quad (5.12)$$

Good stability as a function of plate voltage is achieved if df/dE can be made small. A study of equation 5.12 leads to several possible conclusions, a few of which are listed and discussed:

- a. If $\partial X_2 / \partial f$ is very large the quotient df/dE is small. But $\partial X_2 / \partial f$ may be large only if the Q of L (which is determined primarily by the cavity) is also large.
- b. The quotient df/dE is small if the numerator on the right side of equation 5.12 is also small. A very small numerator can be achieved if each term therein can be individually made to approach zero. It may also be small if different algebraic signs occur among the members such that the algebraic sum of the terms approaches zero.
- c. A positive increment of voltage produces a negative increment of frequency if the numerator and denominator are of the same sign, and a positive increment if they are unlike.

In discussing each of these points individually, (a) needs little further comment inasmuch as a high Q is well known to be a necessary, but not sufficient, requirement for good stability.

Point (b) may be applied to the effect of plate voltage upon frequency stability in the general rather than the specific case. It is first necessary to have a knowledge of the characteristics of the tube involved. These are illustrated ⁽¹⁰⁾ in Figure 5.11.

Note that for large plate currents (indicative of high plate voltage) $\frac{\partial r_p}{\partial I}$ (or $\frac{\partial r_p}{\partial E}$) and $\frac{\partial u}{\partial I}$ (or $\frac{\partial u}{\partial E}$) become very small.

Hence in equation 5.12 the first and second terms may be presumed to become vanishingly small when the tube is operated in regions of

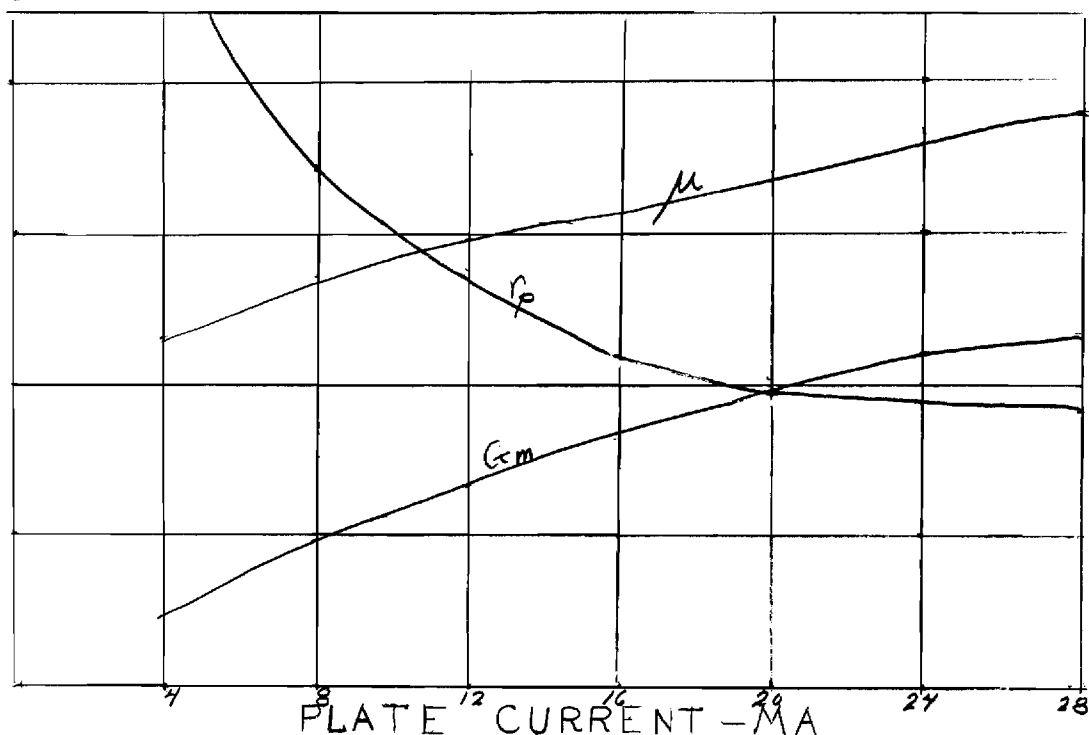


Figure 5.11. Average Characteristics of 6AF4 Triode.

high d-c plate current. A rather similar argument pertains to the last two terms of equation 5.12. It has been shown ⁽⁹⁾ that the rate of change of internal capacitance becomes very small under conditions of high G_m and high plate current. If this is true then the last two terms of the numerator of 5.12 likewise are small. This argument that the numerator decreases rapidly when the plate voltage is raised leads intuitively, at least, to an expected instability versus plate voltage which would follow the same trend. It has actually done so in every case yet tested. This has already been illustrated in both Figure 5.5 and Figure 5.8.

The last point, (c) can be the subject at this time of conjectures only. An analytical expression can be obtained for some of the terms of the numerator, but the effect of voltage upon the interelectrode capacitances is not easily subject to analysis. No experimental data has as yet been compiled on this subject.

It should be remarked that in every case of experimental work on this oscillator that the frequency has increased with increase of plate voltage. In this unstabilized oscillator the change was as large as 4 to 5 Mc at a nominal frequency of 500 Mc

for a plate voltage change of 125 volts.

It is believed that further experimental data may shed considerable light on the factors defying simple analysis particularly on the capacitance effects. A compilation of such data may prove worthwhile as an aid in prediction of optimum configurations for maximum stability.

VI. THE HIGH-ORDER OVERTONE RESPONSE OF QUARTZ CRYSTALS.

During the preliminary work on high-order overtone responses of quartz crystals it has been observed that (a) the relationship between the crystal fundamental and the frequencies of the high-order overtones is not always a simple odd integral relationship: (b) some crystals give more pronounced responses than others; (c) the amplitude of a response is in general a function of the frequency. A study of 10 crystals, with different fundamental frequencies, has been conducted with the purpose of shedding more light on the aforementioned points, specifically of answering the following questions. 1) What relationship exists between the frequency of the crystal fundamental and the frequencies of the observed responses? 2) What are the parameters of a mounted crystal which determine whether or not it is capable of exhibiting strong high-overtone responses? 3) What is the relationship between the amplitude and the frequency of the responses of a given crystal?

The principal component of the apparatus used in conducting this study is the frequency modulated oscillator shown in Figure 6.1. This oscillator is similar in principle to those previously used by this group in their work on nuclear quadrupole resonances. The resonant circuit is a shorted transmission line with a small variable capacitor across the open end providing a means of fine tuning, and a driven capacitor (wobulator) providing the frequency modulation. The output of the oscillator is obtained by conventional means and fed to the vertical deflection plates of an oscilloscope. The frequency range of the oscillator is approximately from 200 Mc to 350 Mc. There is a dead spot in the range from 210 Mc to 230 Mc, and above 290 Mc the oscillator radiates several frequencies simultaneously. However, the latter anomaly in the oscillator's behaviour can, by means of proper measuring techniques, be reduced to nothing more serious than a time consuming annoyance.

The crystal under test was coupled inductively to the resonant line by means of a fixed rectangular loop parallel to and near the line. When the oscillator was swept by the wobulator through an overtone frequency of the crystal a spike, or a differentiated spike, was observed on the oscilloscope. See Figure 6.2a for example.

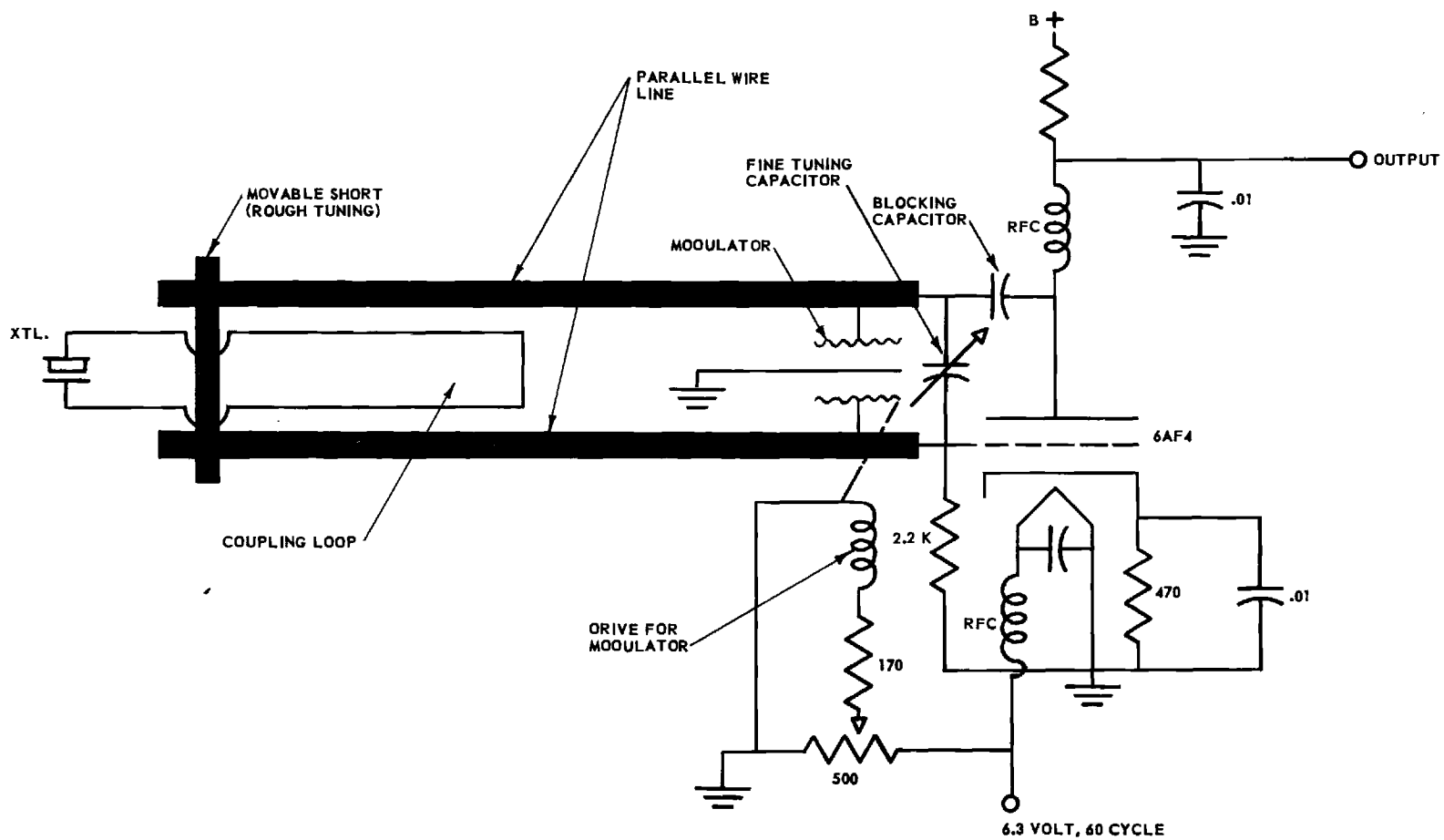


Figure 6.1. Frequency-Modulated Oscillator.

TABLE 6.1

Crystal Designation	Response Frequency (Mc)	Response Amplitude (Millivolts)	Nearest Integral Multiple of Fundamental	Remarks
B-5 AR No. 5	247.3	50	49	Sharp well defined responses
	257.3	25	51	
	267.3	12	53	
	277.3	10	55	
	287.3	5	57	
	297.5	5	59	
B5.02 AR No.3	245.7	100	49	Not as sharp as B-5
	255.7	50	51	
	265.7	25	53	
N6.Mc AR No.1	223.1	29	37	
	235.0	22	39	
	242.3	24	Anomalous	
	246.9	22	41	
	259.0	4	43	
B7.01 AR No. 3	234.3	33	33	
	240.0	15	Anomalous	
	248.4	33	35	
	254.9	8	Anomalous	
	259.9	24	Anomalous	
	262.4	22	37	
	276.5	14	39	
B-9.148 AR No. 3	247.0	43	27	Very sharp responses
	265.1	24	29	
B17.56	240.1	28	14	
28AA	275.1	16	16	
No. 43 25 Mc	274.0	43	11	
	325.3	12	13	
No. 45 25 Mc	274.0	50	11	
	325.0	12	13	
No. 84 36 Mc	261 approx.	50	7	All triple responses. See Fig. 6.2 (c)
	329 "	25	9	
No. 85 36 Mc	261	50	7	
	329	25	9	

To measure the amplitude of the response the height of a spike was first observed. Then a Hewlett-Packard audio oscillator was connected across the transmission line and its output level adjusted until the deflection on the scope was the same as that produced by the signal. The output voltage of the audio oscillator was then measured by a comparison between the deflection it produced when connected directly across the scope to the deflection produced by the internal calibration source of the scope.

The frequency of a response was measured by means of a TS-175/U frequency meter. This meter was tuned until its radiation caused a marker to be superimposed on the oscilloscope presentation of a crystal response. When the oscillator was radiating several frequencies, the marker and the crystal response appeared several times as the tuning capacitor of the oscillator was varied, but they remained superimposed only if they were of the same frequency.

The holder capacitance and the Q of the holder were measured at the same frequency for each of the above crystals with the following results. Tables 6.1 and 6.2 summarize relevant data.

TABLE 6.2

Crystal	Holder Capacitance (mmf)	Holder Q
B-5	4.8	138
B5.02	8.0	72
N6.Mc	11.5	81
B701	7.0	96
B9.148	9.0	81
B17.56	5.7	88
No. 43	9.7	128
No. 45	9.0	139
No. 84	9.0	165
No. 85	7.8	120

During the course of the frequency measurements some photographs of the responses were made. Samples are shown in Figure 6.2. In (a) is shown a typical response of crystal B-5 at 247.3 Mc with the

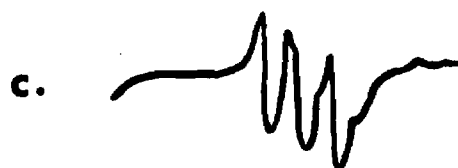
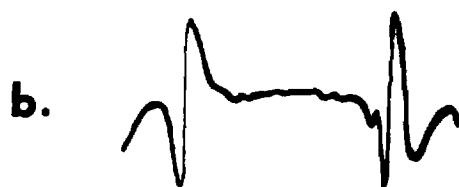
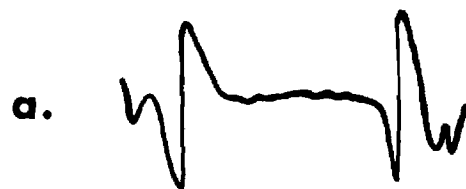


Figure 6.2. Crystal Overtone Responses.

reference marker just to one side of the response. In (b) the same response is shown with the reference marker moved over to the other side. The marker was shifted 0.3 Mc between pictures (a) and (b). Figure 6.2c shows the triple response of crystal No. 84 at 261 Mc. In this oscillogram the horizontal deflection was greatly expanded over its value in (a) and (b).

With regard to the first question, concerning the frequencies of the responses, and in the light of the above data, it is possible to state that with relatively few exceptions the responses occur at frequencies which are very nearly equal to odd multiples of the crystal fundamental. Within the tuning range available in the experiment it appears also that all odd harmonics are capable of being excited. It is true that in some cases (crystals N6.Mc AR No. 1, and B7.01 AR No. 3) responses were observed which did not fit into any simple integral law, and that in one case, crystal B17.56 28AA, it appeared that the even rather than the odd harmonics were being excited, but these comprised relatively few of the total cases studied.

The question of what makes a good high harmonic crystal is much more difficult and has not been answered by these experiments. It was thought that the holder capacitance, or the Q of this capacitance, might well furnish at least a partial answer, but no obvious correlation exists between the data of Table 6.2 and that of Table 6.1.

A qualitative answer to the third question, relating to the dependence of frequency on amplitude, is that, except for the anomalous responses previously noted, the amplitude falls with increasing frequency. The rate of decrease appears to vary from crystal to crystal.

VII. CONCLUSIONS

A compensated brass resonator using a silver-coated Pyrex tubing as center conductor has demonstrated excellent short-term characteristics of temperature stability. It is concluded that if the results can be duplicated in more samples that the techniques employed may produce satisfactory resonators.

Cavity resonators constructed of a ceramic material with extremely low expansion characteristics have to date presented difficult problems of silver plating and of assembly. It tentatively appears that problems of obtaining good conductive surfaces and of effecting low-loss connections during assembly may be disadvantages which will more than offset the attractive temperature characteristics of such ceramic materials.

UHF oscillators utilizing coaxial cavities as reactive elements appear to have attractive possibilities, particularly if the oscillator and resonator are merged into one unit by placing the tube elements on or in the cavity. Stabilities of better than one part per million per volt change of anode voltage appear reasonable of attainment.

Further investigations have been made of high-order overtone responses of quartz crystal resonators. It has been concluded that, with few exceptions, the overtone responses of mounted crystals occur at frequencies which are very nearly equal to odd multiples of the crystal fundamental. It has also been concluded that neither the crystal Q nor its holder capacitance appear to have an appreciable effect upon the magnitude of overtone responses, but the amplitude does decrease with increasing frequency.

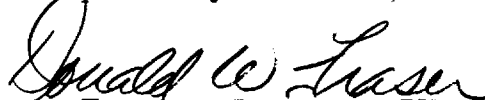
VIII. PROGRAM FOR NEXT QUARTER

The investigation of cavities will be continued. The long-term stability of temperature-compensated cavities will be studied by the comparison, on a long-term basis, of three compensated coaxial cavity resonators which will be designed to have identical characteristics. The ceramic resonator discussed in section IV will undergo further electrical tests. Consideration will also be given to the construction of a cavity which is tunable over a moderate range and which may in addition exhibit satisfactory temperature-frequency characteristics.

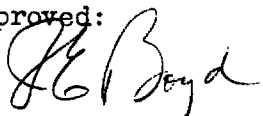
In the field of oscillators the basic type of cavity controlled oscillator discussed in this report will be investigated at frequencies of seven hundred to one thousand megacycles. The factors promoting stability in cavity-controlled oscillators will be a primary basis of consideration.

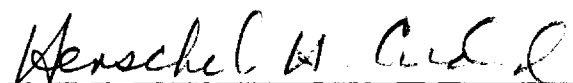
The investigation piezoelectric crystals will be continued, the study to include the response of unmounted units. Consideration will be given to possible methods of utilizing demonstrated overtone responses by achieving oscillator control at frequencies above those now considered to lie within the crystal-controlled oscillator range.

Respectfully submitted,


Donald W. Fraser
Assistant Project Director

Approved:


J. E. Boyd
Head Physics Division


Herschel H. Cudd
Director
Engineering Experiment Station

IX. IDENTIFICATION OF KEY TECHNICIANS

This project is under the direction of Dr. Vernon Crawford who devotes approximately one fourth time to this work. Dr. Crawford is Associate Professor of Physics; he received his Doctor's degree from the University of Virginia and specializes in electromagnetic phenomena. He worked on nuclear quadrupole resonances in connection with station project 171-118, "Investigation of Frequency Control above 150 Mc." Dr. Crawford is presently on a two month's leave of absence but will rejoin the project actively about 1 September.

Mr. Donald W. Fraser is serving as assistant project director. He is Assistant Professor of Electrical Engineering at Georgia Tech and holds the degree of Master of Science in Electrical Engineering from that the same institution. He worked on station project 131-45, "High-Frequency Crystal Controlled Oscillators," devoting approximately one-fourth time thereto. His other experience includes five years of electronic testing and research in the U. S. Navy. Mr. Fraser is currently devoting full time to this project.

Mr. James C. Sellers joined the project as Electronics Technician at its onset. He is currently devoting full time to the project. Mr. Sellers previously was engaged for eight years in nuclear instrumentation with AEC at Oak Ridge, Tennessee where he had extensive experience as a technician in design, assembly, and testing of electronic circuits.

Mr. James C. Hogg, Jr., Assistant Research Professor, devotes approximately one-fourth time to this project. Mr. Hogg holds the degree of Master of Science in Electrical Engineering from the Georgia Institute of Technology. Mr. Hogg has had extensive experience in circuit design and oscillators both in the industrial and the research field. He was employed on a full time basis on the S.C.E.L. projects "High Frequency Crystal Controlled Oscillator Circuits" and "Investigation of Frequency Control above 150 Mc."

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ENGINEERING EXPERIMENT STATION
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Atlanta, Georgia

PROGRESS REPORT NO. 3

PROJECT NO. 229-198

PRECISION FREQUENCY CONTROL TECHNIQUES
(500 mc and Higher)

By

VERNON CRAWFORD and DONALD W. FRASER

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CONTRACT NO. DA-36-039-sc-42590

DEPARTMENT OF THE ARMY PROJECT: 3-99-11-022
SIGNAL CORPS PROJECT: 33-142B

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AUGUST 1, 1953, TO NOVEMBER 1, 1953

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I. PURPOSE

The purpose of this project is threefold; (a) to continue work on the stabilization of oscillators between 500 and 3000 mc, using cavity resonators, (b) to investigate any new phenomena of resonance that occur in the range of 500 to 3000 mc and which may show promise of some success, and (c) to undertake any other investigations which may arise during the course of the work outlined in (a) and (b) above or which may be mutually agreed upon between the Contractor and the Contracting Office or his representative.

By agreement with the sponsor, investigations of resonances below 500 mc may be prosecuted as preliminary steps in determining the feasibility of frequency control by the phenomena under study. In addition, cavity resonators previously under construction, and designed to provide control of frequencies below 500 mc, may be completed and tested as aids in perfecting measurement techniques which will later be applied to the range of frequencies above 500 mc.

II. ABSTRACT

During the present quarter the principle of temperature compensation, previously applied to coaxial cavities resonating at 300 megacycles, has been extended to resonators designed for the 600-megacycle range. Variations in construction from the earlier models have been included. These changes correct previous deficiencies brought about by unequal mass-to-area ratios of resonator and compensating section and by mechanical instabilities of soldered joints. A total of three cavities designed to operate at nearly identical frequencies and to exhibit similar temperature characteristics have been built and are undergoing tests. A fourth cavity which may, in addition, be tuned over a moderate frequency range is in the design stage.

Considerable investigation of cavity-controlled oscillators has been conducted. An analytical investigation of the input admittance of a loop-coupled cavity has been made. Curves of input conductance, susceptance, and phase angle are presented as tools which are useful in the design of cavity-controlled oscillators. The effects of various types and lengths of couplings are considered, and one oscillator which minimizes lead lengths is shown in photographs. A cavity-controlled oscillator operating in the 300-megacycle range has been exposed to extensive temperature variations in a temperature-controlled chamber and is shown to exhibit frequency stabilities essentially equivalent to that of the cavity alone.

Further investigations on the high overtone responses of quartz crystals have been carried out. Unmounted crystal blanks have yielded weak responses in the 200 to 300-mc region. Impedance measurements of circuits embodying crystals have been attempted without success. Discriminator circuits have been constructed in which the overtone response of a crystal governs the slope of the discriminator output curve. A beginning has been made in the search for the most satisfactory method of control of driving frequency by discriminator output.

III. CONFERENCES

Representatives of the Signal Corps Engineering Laboratories visited this project at the Georgia Institute of Technology on September 16-17, 1953, for the purpose of reviewing the program in progress here. The individuals comprising the reviewing party were Prof. K. S. Van Dyke, Mr. R. A. Sykes, and Dr. E. A. Gerber. All pertinent details of the project were explained to the visiting party. Several suggestions were offered by members of the group. Mr. Sykes suggested that consideration be given to the use of fused quartz in construction of cavity resonators. Prof. Van Dyke suggested that the study of overtone responses of quartz crystals presently being conducted in the 300-mc region be supplemented by attempts to measure the crystal parameters in the same frequency range. Dr. Gerber suggested, in conjunction with this same thought, that the best possible crystals of high fundamental frequency should be made available and further suggested that the Contracting Officer's Technical Representative should be contacted with a request to furnish such crystals. The conference was completed by a visit to the project laboratory where the group were able to survey the laboratory equipment and to observe experimental work in progress.

A month later, on October 20 and 21, Mr. O. P. Layden of Squier Signal Laboratory visited the project. Serving in the capacity of the Contracting Officer's Technical Representative, he reviewed the laboratory operation, the experimental work in progress, and observed the results of the research prosecuted during the first eight months of the contract. Discussions of probable objectives during succeeding months completed the conference.

IV. COAXIAL CAVITY RESONATORS

It was pointed out in the first report submitted by this project (1), and it was emphasized in a subsequent report (2), that experimental work on coaxial cavities would have as a specific objective the construction of resonators which should be relatively insensitive to variations of ambient temperature. A secondary objective was to be the attainment, or improvement, of other characteristics which could influence the frequency stability of oscillating systems. In particular an examination was to be made of circuits in which a resonant cavity is the primary frequency-determining element. In such a circuit the characteristics named could include cavity Q, cavity impedance, and mechanical stability. These latter properties are influenced, or are determined, by choice of materials, by methods of coupling, and by selection and control of the dielectric which fills the space between the inner and outer conductor.

A resonator which displayed attractive characteristics was described (2). It consisted of a coaxial cavity, designed to resonate at 300 mc, which utilized a silver plated brass tube as an outer conductor and a silver-plated Pyrex tube as an inner conductor. A temperature-compensating section was added to reduce the effects of temperature variation upon the resonant frequency of the cavity. The results of fairly extensive short-term tests showed that the resonator demonstrated a frequency change of about 0.5 parts per million per degree centigrade change in ambient temperature. One long-term test yielded essentially identical results.

During the present quarter the temperature-compensation principle has been extended to resonators designed for the 600-mc range. Some variations in construction have been applied with a view toward improving certain minor deficiencies appearing in the earlier model. A total of three cavities designed to operate at the same frequency and to exhibit similar temperature characteristics has been built, and they are undergoing tests. A fourth cavity which may, in addition, be tuned over a moderate frequency range is in the design stage.

Cavities formed from the ceramic Stupalith have to date not proved satisfactory because of difficulties in assembly. This problem is discussed in the last portion of this section. Other means of construction which may improve the situation are considered and discussed.

A. Modified Compensated Brass Resonator

The temperature-compensated brass resonator described in the previous report (2) demonstrates an apparent thermal "lag" when subjected to rapid heating or cooling. It is believed that this effect is caused by unequal mass-to-area ratios of the resonator proper and of the compensating section.

A modified type of resonator in which these mass-to-area ratios should be substantially constant is illustrated in Figure 4.1. This cavity has, in addition, several other features which are believed to be superior. The compensating section, which extends from the inner face of insert plug A to the point of contact of the center conductor on insert plug B, may be varied in length by adjusting B, which may be screwed in or out. Some correction for experimentally determined errors in compensation may thus be effected. A change in resonant frequency occurs when the length of the compensating section is changed; hence, some compromise between the desired frequency and the optimum compensation is necessary. Another innovation in this cavity is illustrated by plug A, i.e., electrical sealing is produced by mechanical pressure of the plug against the inner collar of the outer conductor. In the earlier model this joint was sealed with solder. The new model will not incorporate the mechanical instabilities often observed in soldered joints, but it remains to be proved that the metal-to-metal joint will provide satisfactory electrical contact.

Three cavities, as nearly identical as construction permits, have been assembled. Tests of these cavities are being initiated, and it is contemplated that data will be accumulated over a period of several weeks. The assembled data will, it is hoped, resolve several as-yet-unanswered questions. These include queries as to the uniformity of action of mechanically identical cavities, questions of comparison of long-term versus short-term stability, and the effects of repetitious temperature cycling. It is believed that sufficient information will be gathered prior to preparing the next report to permit including definite conclusions.

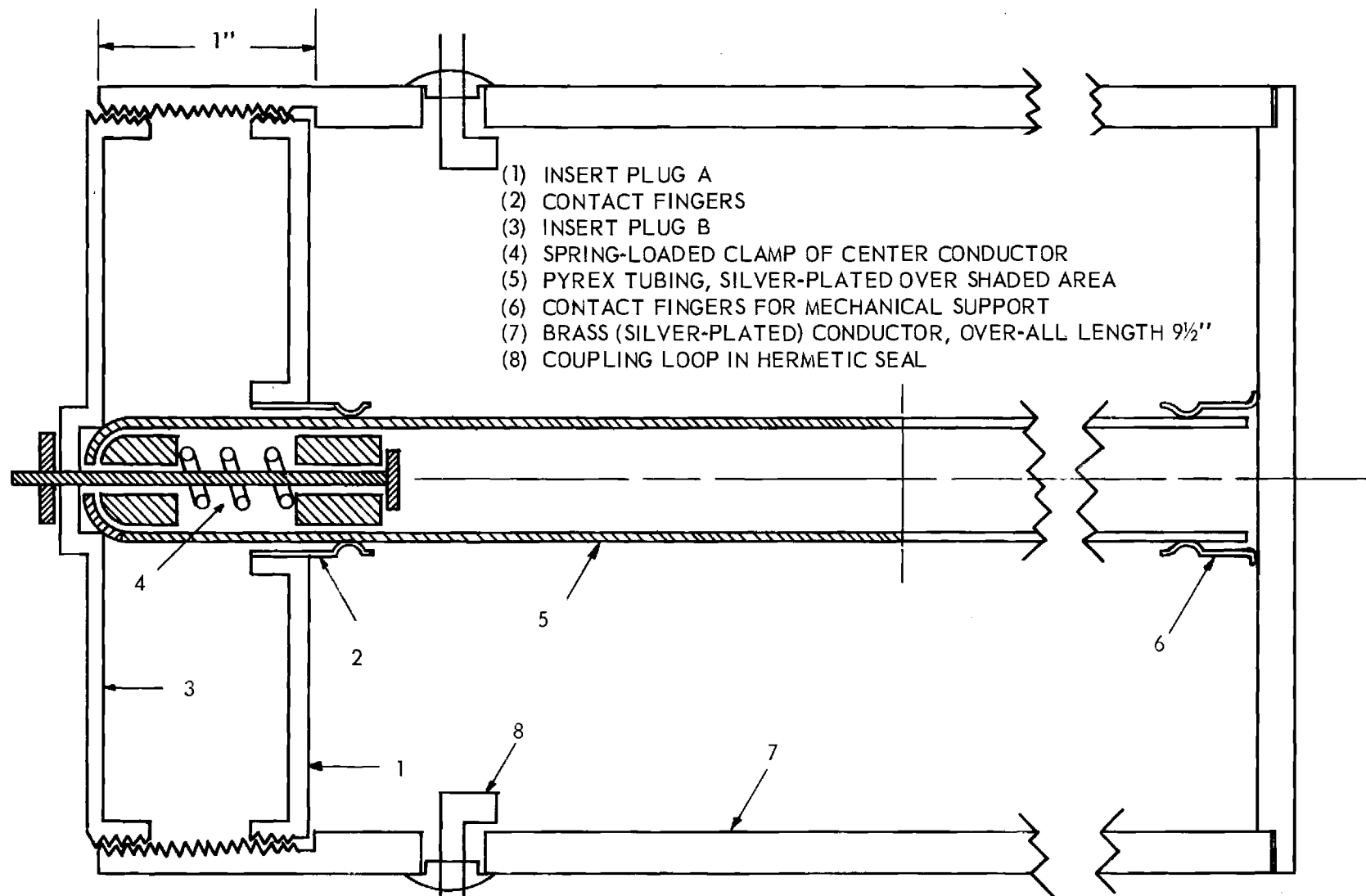


Figure 4.1 Temperature-Compensated Brass Resonator.

B. Tunable Compensated Cavities

At the present time the best prospects of reducing temperature effects appear to lie in the compensated cavity. Those cavities thus far constructed, however, have been designed for single fixed frequencies. The obvious desirability of making the cavity tunable leads to consideration of practical means of incorporating such a characteristic without adversely affecting the otherwise desirable properties of the resonator. It has, for example, been pointed out previously that hermetic sealing is required if the resonator is not to be affected by the variable humidity of the atmosphere. A tuning device, then, should be of a type which can be incorporated within, or make connections to, the sealed resonator. The most widely used type of tuning element is the coaxial-line plunger whose method of use is well known and has been adequately treated (3, 4). It has the obvious disadvantage, however, that considerable mechanical movement may be difficult to achieve if the plunger is within a sealed space. The use of flexible bellows, in a manner comparable to that in Figure 4.2, as will be described in the succeeding paragraph, is a possible solution. The utilization of a variable capacitor, shunted across the coaxial line at a selected point, may also be considered, particularly in view of the fact that hermetically sealed, low-loss variable air capacitors are available as standard stock items.

One method by which a tunable cavity may be constructed without adverse effect on either its temperature characteristics or the tightness of its hermetic seals is shown in Figure 4.2. A spring-loaded flexible bellows permits movement of the center conductor under influence of the end-cap and at the same time retains hermetic sealing. With the bellows at maximum extension, as illustrated, the resonant frequency of the cavity is a maximum. If the end-cap is screwed into the tubing the length of the electrically active portion of the center conductor is increased and the frequency therefore reduced. The length of the compensating section L should be adjusted to produce optimum compensation at the center frequency around which the cavity is to tune.

A tunable cavity of this type may normally be considered as applicable to the relatively narrow frequency band rather than to a broad one. A tuning range of ± 5 per cent is reasonable; a greater range would require greater complexity of methods of controlling mechanical movement.

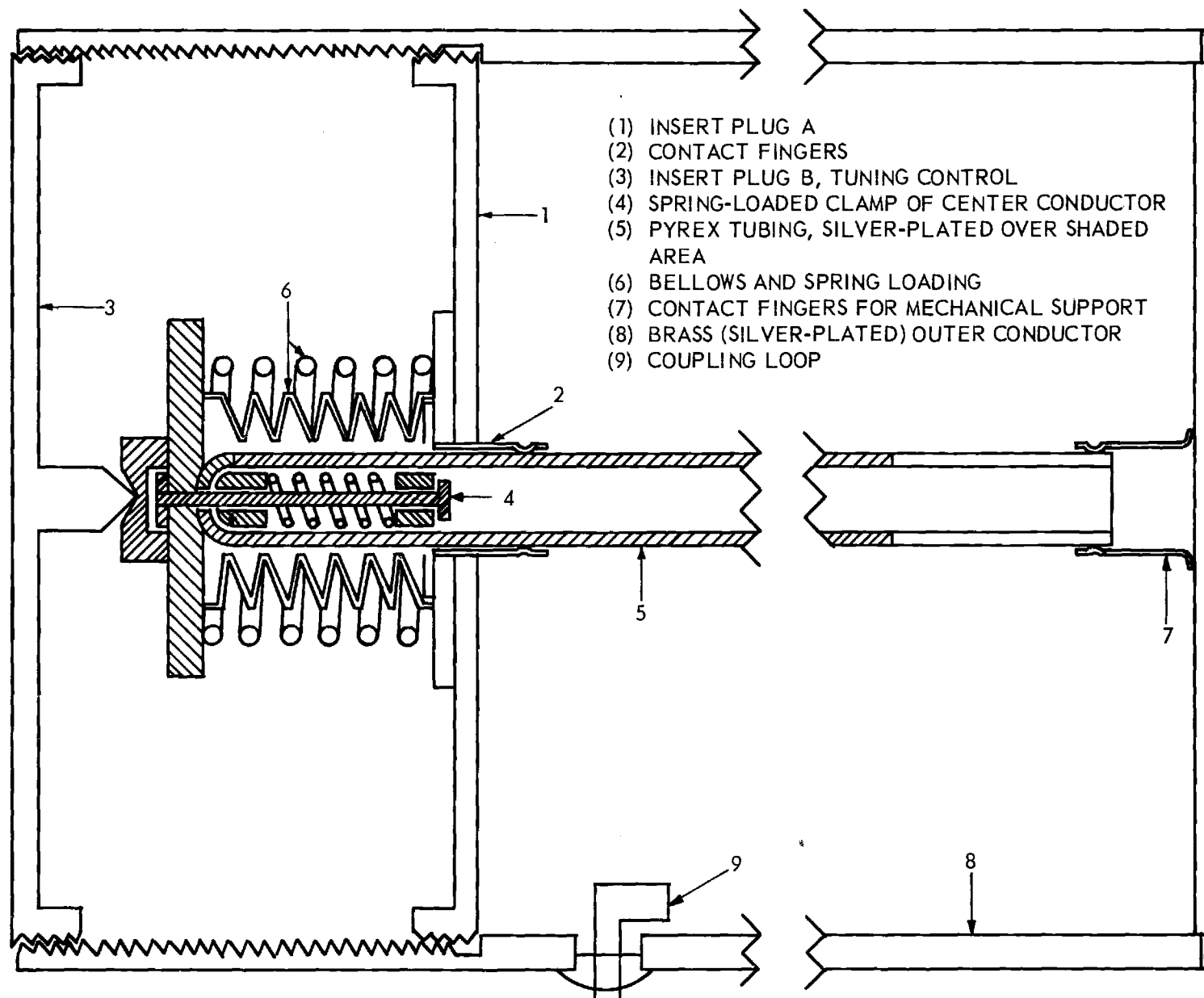


Figure 4.2. Tunable Compensated Cavity.

The cavity illustrated is in the design stage; it is anticipated that it will be completed as described and that tests will be conducted with it during the next quarter. Another method of tuning previously mentioned, involving the use of a variable capacitor at a prescribed point along the line, will be investigated by modifying the existing cavities.

C. Cavities of Ceramics or Allied Materials

The construction of a cavity composed of the ceramic Stupalith has been described previously (2). Although considerable difficulty was encountered in adding a suitable conductive coating to the ceramic, a process for fixing fired and electroplated silver surfaces was achieved and was described. Another serious difficulty has arisen during the subsequent attempts to assemble a completed resonator. The trouble apparently originates in the porous structure of the ceramic; it is evidenced by a pulling off of silvered surfaces when they are subjected to the heat required to solder abutting surfaces. This "peeling" tends to occur even when solders of very low melting points are used. Close examination of the peeled-off layer reveals the presence of many tiny particles of the ceramic on the underside. Apparently, then, the fault lies in the weakness of the porous ceramic rather than in the adhesive properties of the silver plating.

A possible solution lies in the adoption of other means of affixing conductive coating. One method which will be investigated is first to sputter a fine film of a basic conductive material, such as copper, upon the ceramic, and then to silver plate on this base. It is believed that a more secure metal-to-ceramic bond may thus be achieved.

The adoption of other materials with small temperature coefficients is under consideration. The possibilities include fused quartz and nickel-steels. It may be possible to construct a complete resonator of a single piece of quartz, while the nickel-steel Invar appears to be more suited for use as center conductors only.

V. CAVITY-CONTROLLED OSCILLATORS

In the previous report it was stated that coaxial cavities may serve adequately to stabilize uhf oscillators if a proper selection of circuit configurations and of coupling methods is made. In one configuration the cavity serves as a link in the positive feedback loop of a grounded-grid amplifier; in another the cavity serves as a reactive element shunted between two elements of a triode oscillator. The latter configuration served as a primary basis for the investigations reported upon. The same circuit arrangement has undergone continued study particularly from the standpoint of the effect of coupled impedances and is discussed further in subsequent paragraphs. A study of the input admittance of a loop-coupled cavity is included. This admittance serves as the primary frequency-determining parameter in the circuit configurations under investigation; therefore, data on its variations become an important design consideration.

Methods and points of coupling are considered. It has been pointed out previously that adequate controlled coupling is difficult to obtain at uhf, that the electrical length of connecting lines, probes, and feed-throughs may, in spite of all precautions, become of sufficient magnitude to affect seriously the frequency determining ability of the cavity. The problem is less severe when the tube base may be incorporated in the cavity. However this arrangement is not satisfactory, at least without modification, in a cavity which is to be hermetically sealed. Possible alternative methods are described.

The results of tests on several oscillators, ranging in frequency from 300 mc to 700 mc are given. This includes the effects of temperature variation upon an oscillator whose frequency determining element, exterior to the tube, is a temperature-compensated coaxial cavity.

A. Input Admittance of a Loop-Coupled Cavity

The analysis of the input admittance of a cavity must include the physical coupling link, whatever its configuration. Inasmuch as inductive coupling by a closed loop is widely used, the succeeding discussion applies to such a configuration. The results may, however, be applied to any type of coupling where in the coupling link exhibits an admittance comparable to that of the closed

inductive loop. For a complete analysis of the parameters introduced by various types of coupling the reader is referred to Beringer (5).

The analysis is started by assuming that the loop-coupled cavity may be represented as shown in Figure 5.1. In this figure L_2 , C_2 and R_2 represent the equivalent inductance, capacitance and losses of the cavity, while L_1 and R_1 represent the inductance and losses of the coupling loop.

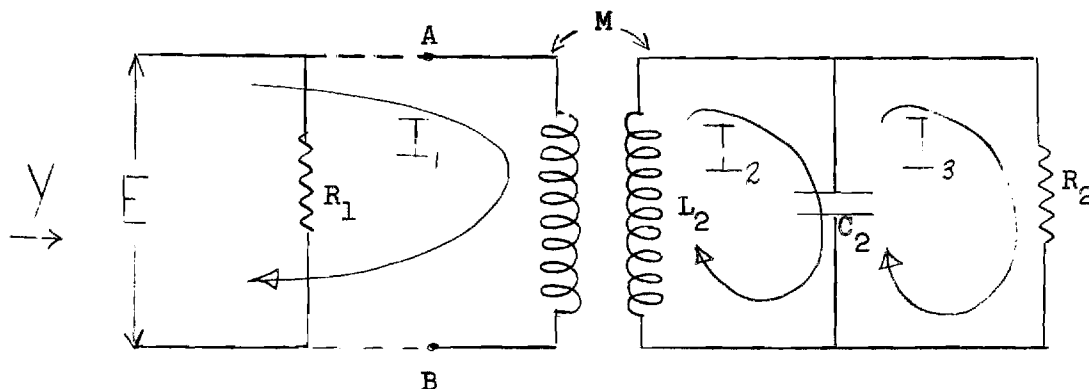


Figure 5.1. Equivalent Form of Loop-Coupled Cavity.

A number of useful parameters are introduced. These are defined in Table I.

TABLE I
NOTATION

$k = M/\sqrt{L_1 L_2}$	Coupling coefficient
$\omega_2 = 1/\sqrt{L_2 C_2}$	Resonant frequency of secondary
$Q_1 = R_1/\omega_2 L_1$	Primary Q
$Q_2 = R_2/\omega_2 L_2$	Secondary Q
$m = 1 - k^2$	Useful dimensionless factor
$Y = G + jB$	Input admittance
$\phi = \tan^{-1} B/G$	Phase angle of admittance
$k_c = \text{critical } k$	
$X = \omega/\omega_2$	

The input admittance at terminals A and B may be determined by a straightforward application of Kirchhoff's Laws. From the first law

$$\begin{aligned} I_1(j\omega L_1) - I_2(j\omega M) &= E \\ -I_1(j\omega M) + I_2\left(j\omega L_2 + \frac{1}{j\omega C_2}\right) - I_3\left(\frac{1}{j\omega C_2}\right) &= 0 \\ -I_2(j\omega C_2) + I_3\left(R_2 + \frac{1}{j\omega C_2}\right) &= 0. \end{aligned} \quad (5.1)$$

If this equation is solved for I_1 , and the quotient E/I_1 is taken, there results

$$Y_{AB} = \frac{1 + j(\omega R_2 C_2 - R_2/\omega L_2)}{\omega L_1 \left[\frac{\omega^2 M^2 R_2 C_2}{L_1 L_2} - \omega R_2 C_2 + R_2/\omega L_2 + j\left(1 - \frac{M^2}{L_1 L_2}\right) \right]} \quad (5.2)$$

Considerable simplification may be obtained by introducing several definitions from Table I. Equation 5.2 then becomes

$$Y_{AB} = \frac{1 + jQ_2\left(x - \frac{1}{x}\right)}{\omega_2 L_1 \left[Q_2(1 - x^2 m) + jxm \right]} \quad (5.3)$$

The effect of the losses in the loop may be taken into account by the addition of $1/R_1$ to this expression. It is now helpful in the analysis to convert the equations to a dimensionless (normalized) form by multiplying both sides of equation 5.3, with the loss term added, by $\omega_2 L_1$ to obtain

$$Y\omega_2 L_1 = \frac{1 + jQ_2\left(x - \frac{1}{x}\right)}{Q_2(1 - x^2 m) + jxm} + \frac{1}{Q_1} \quad (5.4)$$

Careful consideration was given to various means of interpreting this final equation. It was finally decided to substitute numerical values of Q_1 and Q_2 , values which would be representative of the resonances now under study. A value of 100 was selected for Q_1 ; that for Q_2 was 1000. This latter number is somewhat lower than may be expected from a coaxial cavity, even if heavily

loaded, but an appraisal of equation 5.4 shows that variation of Q_2 is reflected almost directly as an equivalent scale factor. Therefore, curves of admittance plotted against the frequency variable may be easily applied to other values of Q_2 .

Figures 5.2, 5.3 and 5.4 represent the various component parts of the input admittance: susceptance, conductance and phase angle in the case of $Q_1 = 100$, $Q_2 = 1000$. The parameter selected is the coefficient of coupling k ; it in turn is represented both numerically and in terms of the critical coefficient of coupling k_c .

The information displayed in these figures provides a further tool in the design of a cavity-controlled oscillator. If the data presented here are combined with formulas for evaluating coupling and cavity characteristics, the actual admittance at the input terminals may be computed with some accuracy. The formulas have been discussed in previous reports (1, 2) and are more completely covered in other references (6, 7).

B. Methods of Coupling an Oscillator to a Cavity

The analysis of the previous section leads to values of admittance at the actual input to the cavity. In practice, it may be difficult to place the pins of the oscillator's vacuum tube at the true input. The 500-mc cavity-controlled oscillator described in the previous report (2) did achieve this pin position by mounting the tube base in the end wall of the cavity. In this position values of input admittance, as measured on an r-f bridge, compared favorably with values computed by methods of the previous section. It was not difficult to achieve cavity control of oscillations, and the oscillator, when under cavity control, exhibited good stability.

If the cavity is to be hermetically sealed, a more logical method of mounting the tube exists. This is to attach it to the coupling loop by means of leads which have access to the cavity through a hermetic seal. But this method, although mechanically sound, may be unsatisfactory electrically. The leads in the hermetic seal, added to those between the seal and tube pins, may contribute leakage inductance of sufficient magnitude to so alter the input admittance characteristics that cavity control becomes either poor or impossible. This phenomenon has been observed several times; in the case of a 500-mc

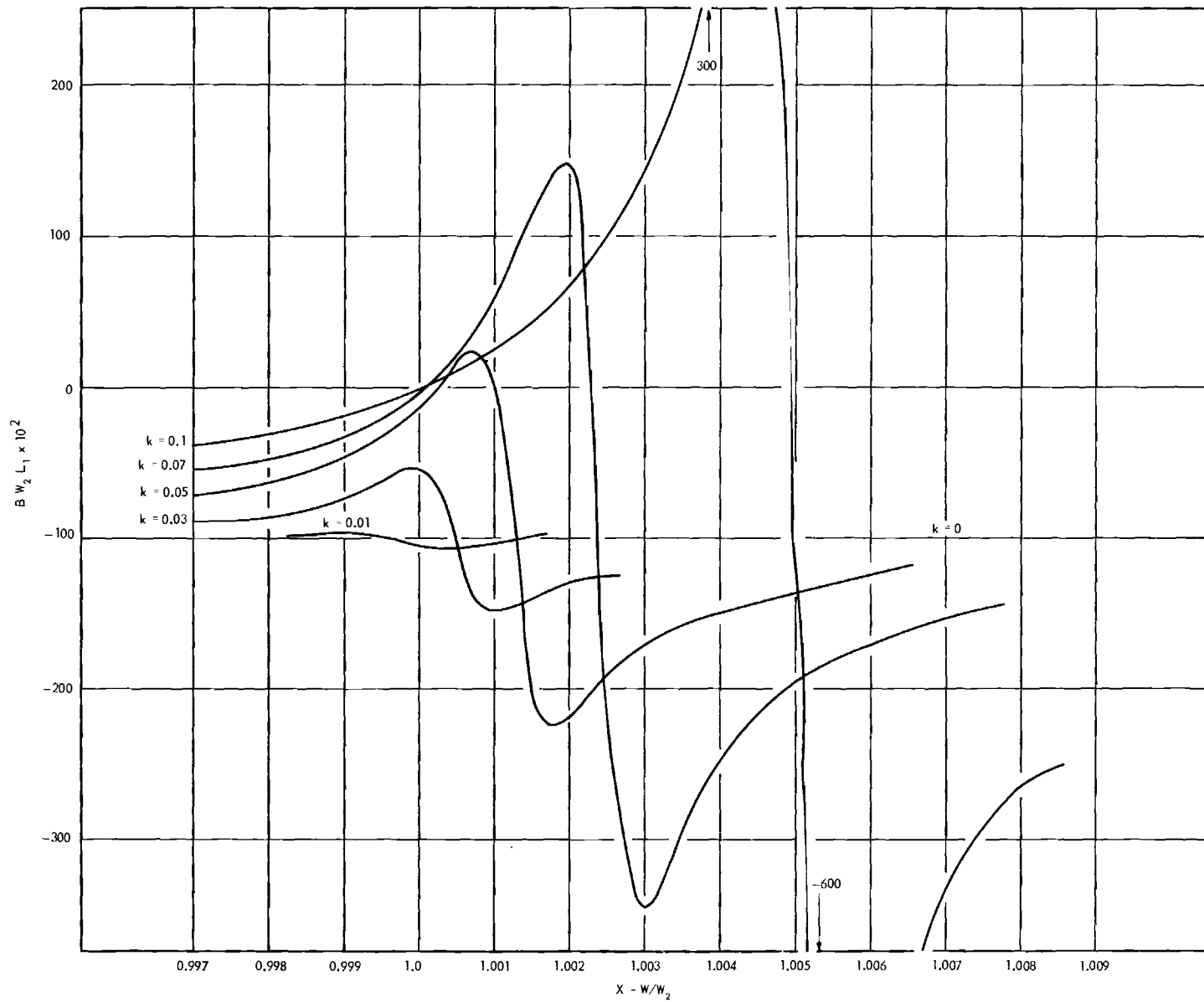


Figure 5.2. Input Susceptance of a Loop-Coupled Cavity.

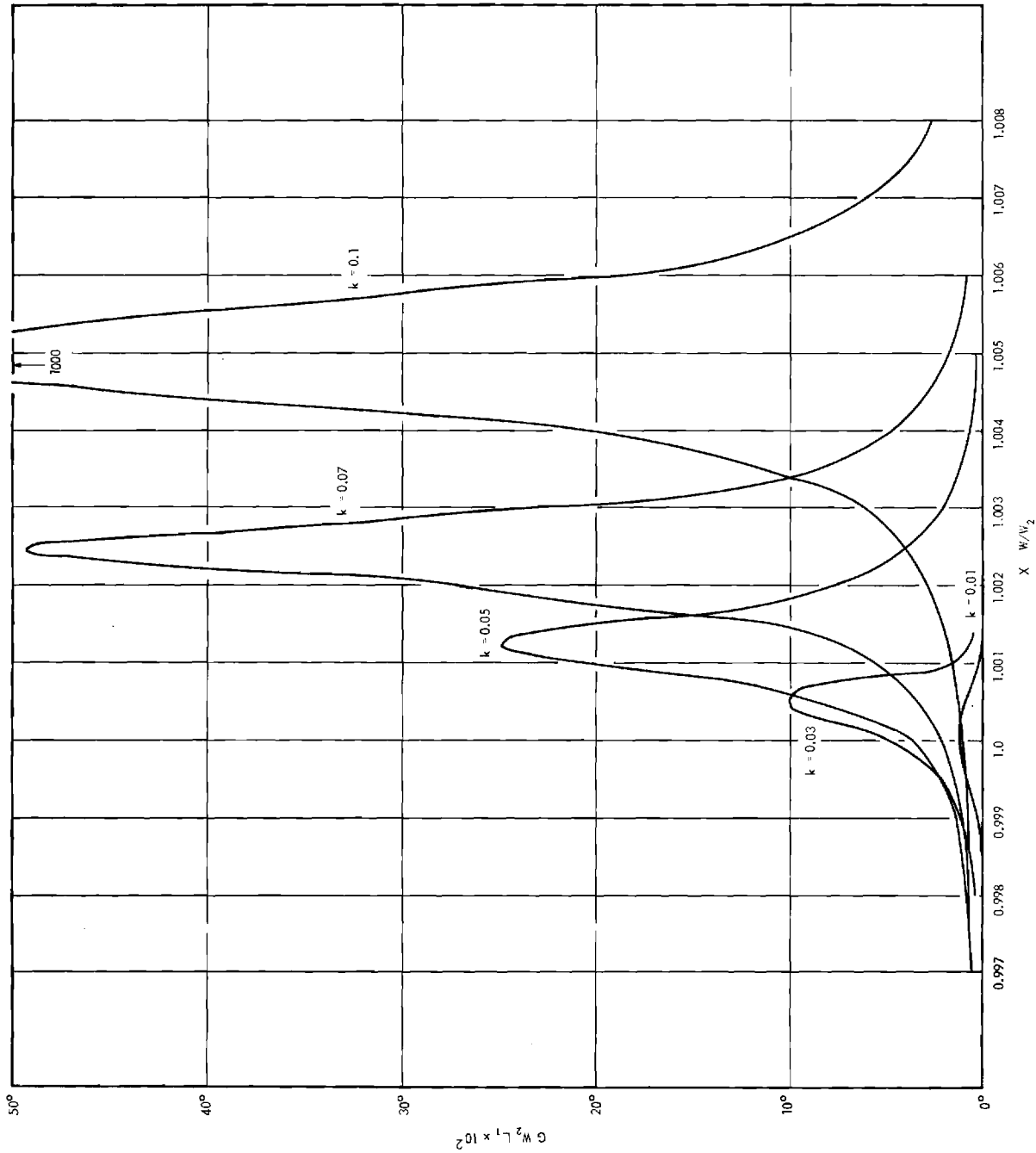


Figure 5.3. Input Conductance of a Loop-Coupled Cavity.

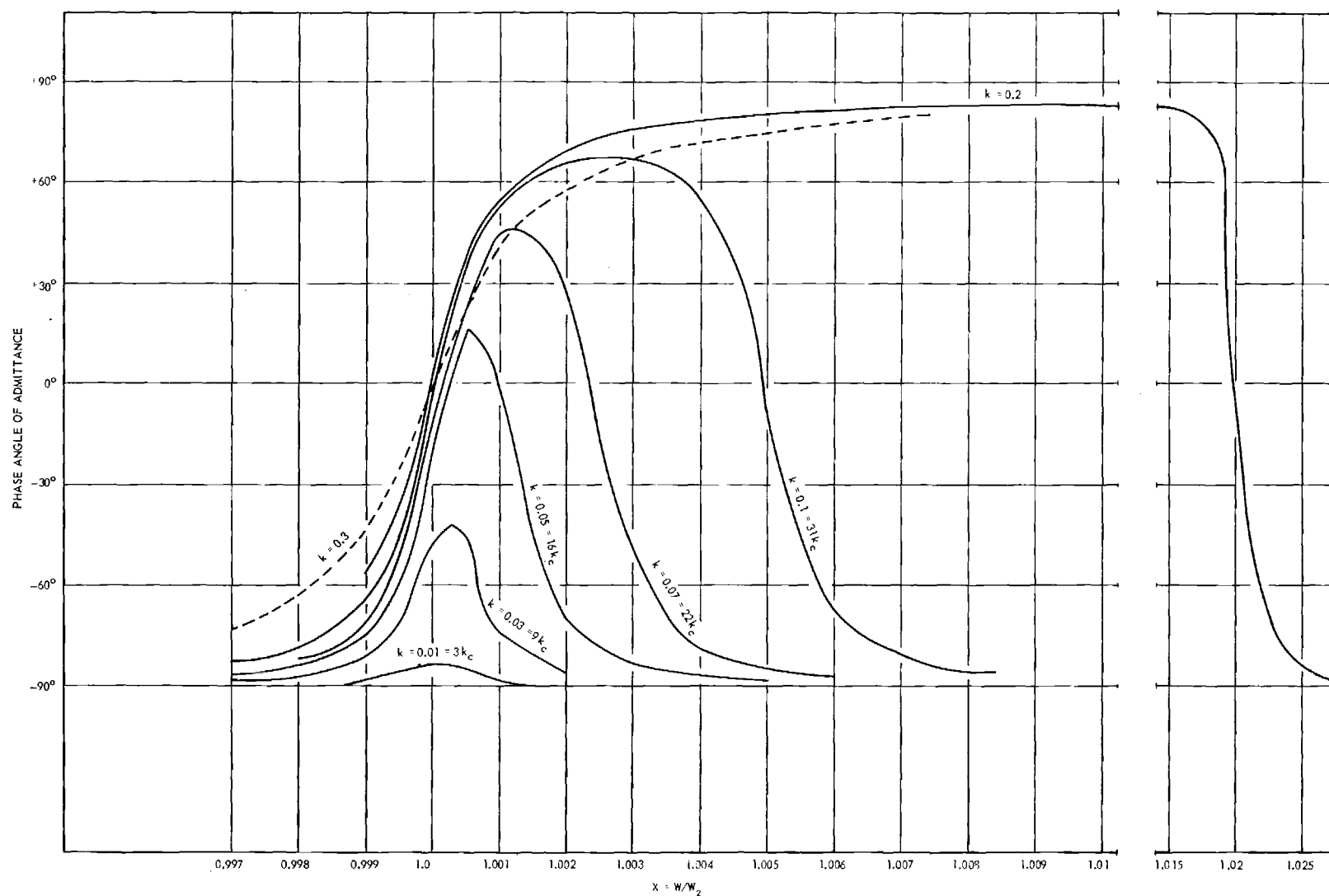


Figure 5.4. Phase Angle of Input Admittance.

oscillator, instabilities as small as 0.5 part per million per volt change of anode potential (ppm/volt) were realizable if the tube pins were within the cavity, but instabilities not smaller than 3 ppm/volt resulted when the coupling was effected via leads passing through a hermetic seal.

A possible compromise between the two methods is illustrated in the photographs of Figures 5.5, 5.6 and 5.7. The tube socket is replaced by pin clamps; the plate and grid pins are soldered directly to the pins of the hermetic seal. In this manner the leakage inductance is reduced considerably below that which would exist if a conventional tube base were used. This arrangement simplifies the problem of achieving cavity control. A cavity-controlled oscillator of this type, operating at 400 mc, exhibited an instability of about 1.5 ppm/volt.

Another method of coupling which has been considered is the conductive method. In this method the plate and grid are each tied directly (except for d-c isolation) to the cavity, one to the inner and one to the outer conductor. This is illustrated in Figure 5.8 where the cavity is represented by a shorted line as an electrical equivalent.

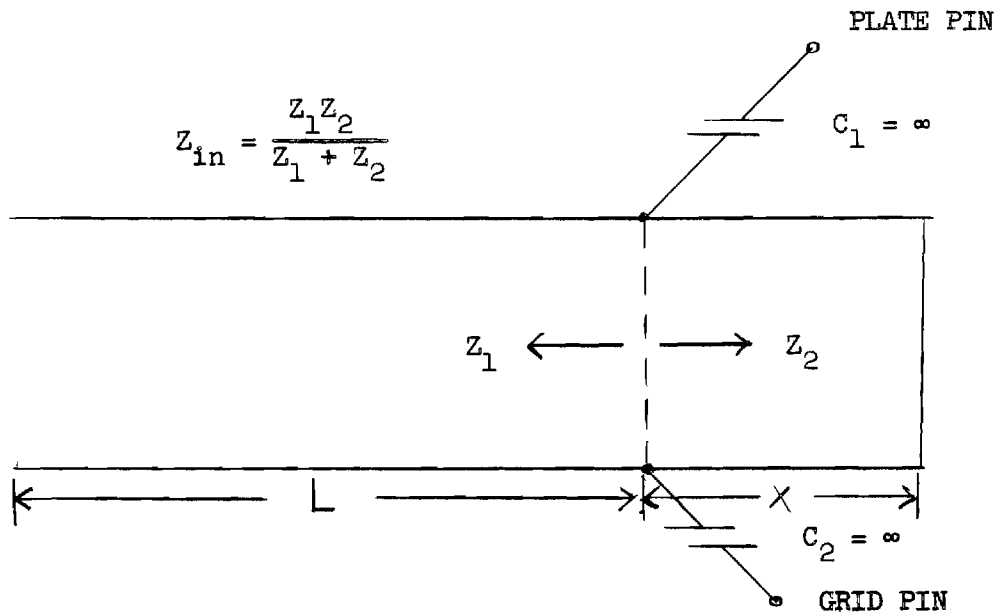


Figure 5.8. Conductive Coupling to Cavity.

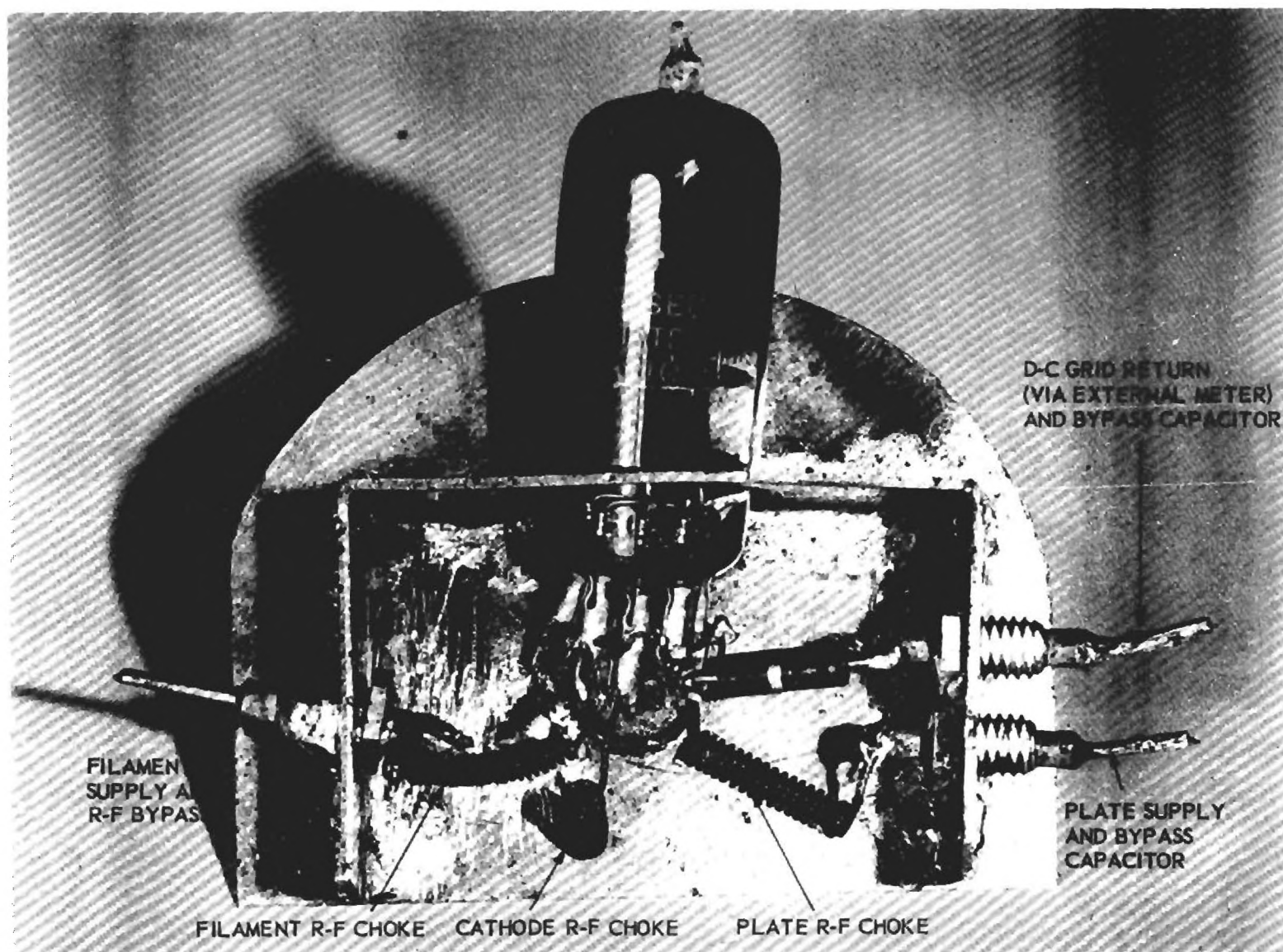


Figure 5.5. Oscillator Minimizing Lead Length (Top View).

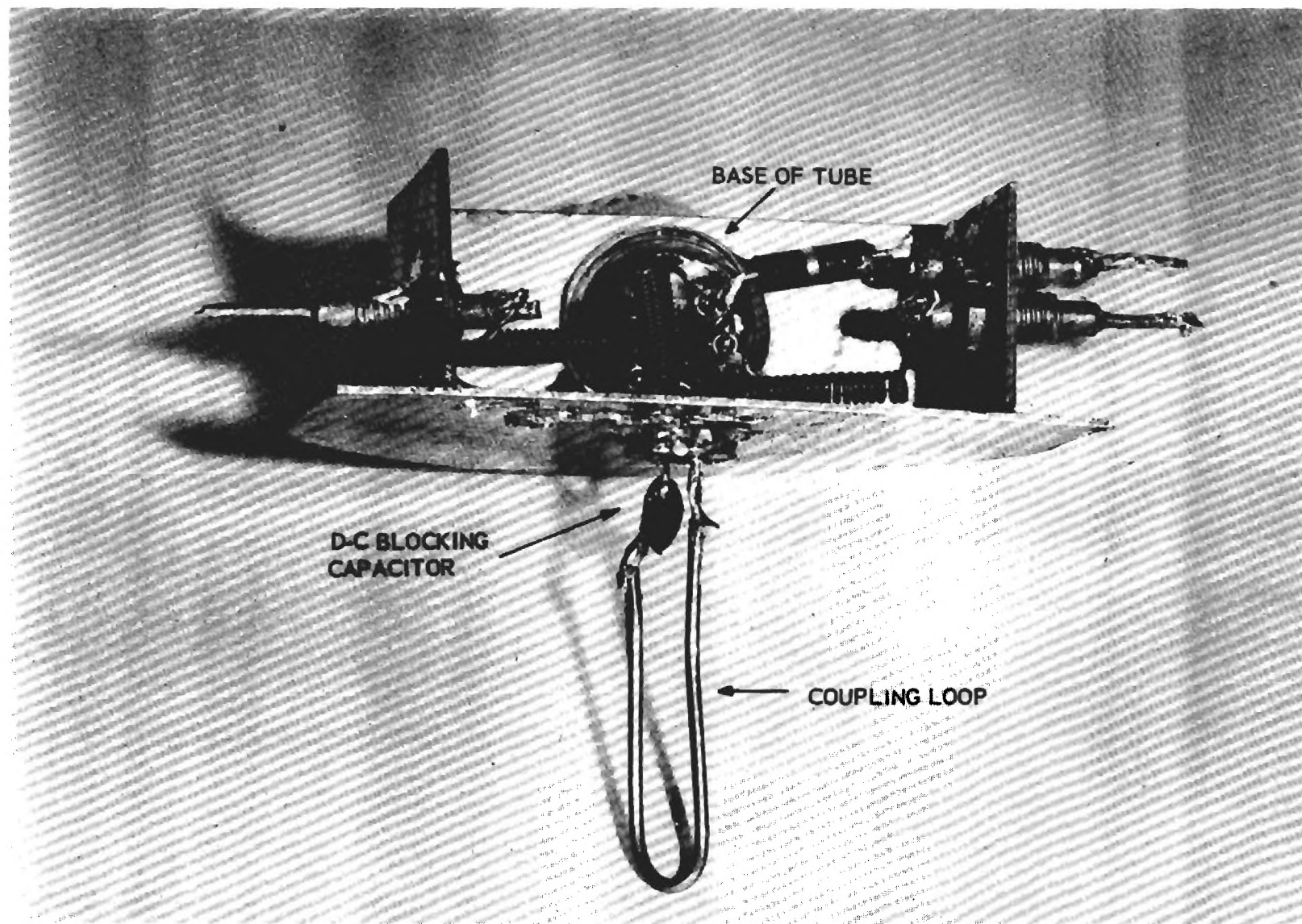


Figure 5.6. Oscillator Minimizing Lead Length (Side and Bottom View).

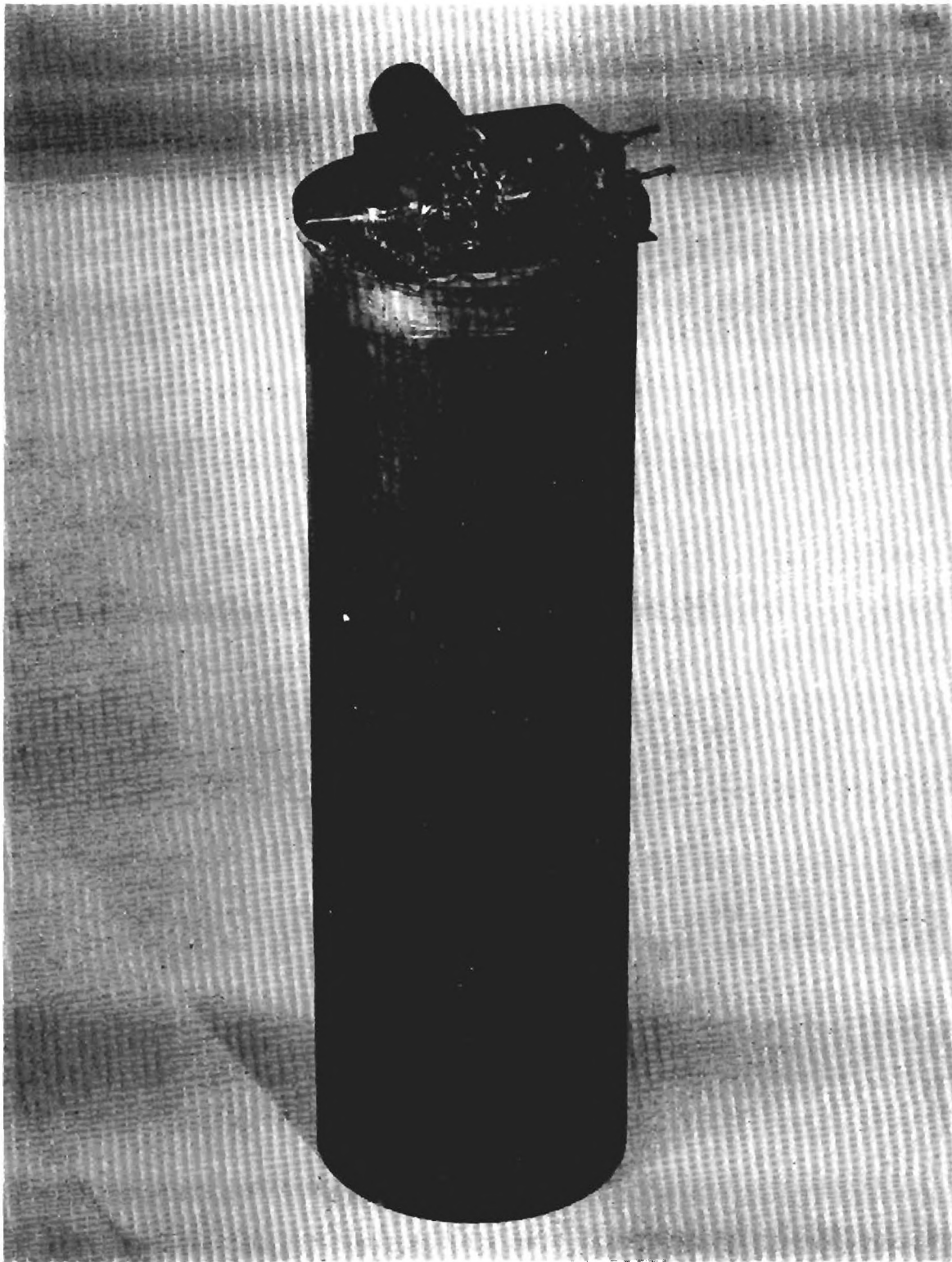


Figure 5.7. Oscillator Attached to Coaxial Cavity.

The impedance between grid and plate is a maximum at the open end where it equals $jZ_0 \tan \frac{2\pi l}{\lambda}$. At all other points it is the parallel combination of Z_1 and Z_2 . In theory the impedance should become very small as x becomes small, and the oscillator should cease to run because of insufficient plate to grid impedance. In practice a completely different phenomenon has been frequently observed: As the length x is decreased from L , the frequency of oscillation rises smoothly (as may be predicted by simple calculation of Z_{in}) until x becomes quite small. At some point, not definable analytically, the frequency may jump discontinuously to a much higher frequency. Observations indicate that at this new frequency the oscillator is running on the impedance Z_2 (that of the shorted end alone). The length $L - x$ apparently loses excitation as shown by the observation that it may be grounded, shorted or otherwise disturbed without materially affecting the oscillator.

The same tendency of an oscillatory feedback path occurring around the shorted end is, unfortunately, more pronounced in the cavity than in the open line. A sketch of a test carried out on an open wire line at relatively low frequencies, shown in Figure 5.9, will best illustrate the factors involved. The dimensions of Figure 5.8 apply.

It will be seen that, as the length x was reduced until x/L approached 0.06, the instability became progressively less. But, as x/L approached 0.05 the frequency of oscillation jumped discontinuously from 223 to 352 mc and simultaneously the instability increased almost tenfold from 7.5 to 66 ppm/volt.

The tendency of the oscillator to jump from a stable lower-frequency position to an unstable higher frequency has been, as was previously remarked, more pronounced in the case of coaxial cavities than in that of open lines. Furthermore, there is an obvious problem involved in mounting the tube if its plate pin, or its grid pin, is to connect to the inner conductor by means of an extremely short lead (in order to minimize leakage inductance).

One configuration which facilitates mechanical mounting entails inductive coupling at the end of the cavity. If the coaxial arrangement included an outer conductor which is longer than the inner conductor, the tube base may be

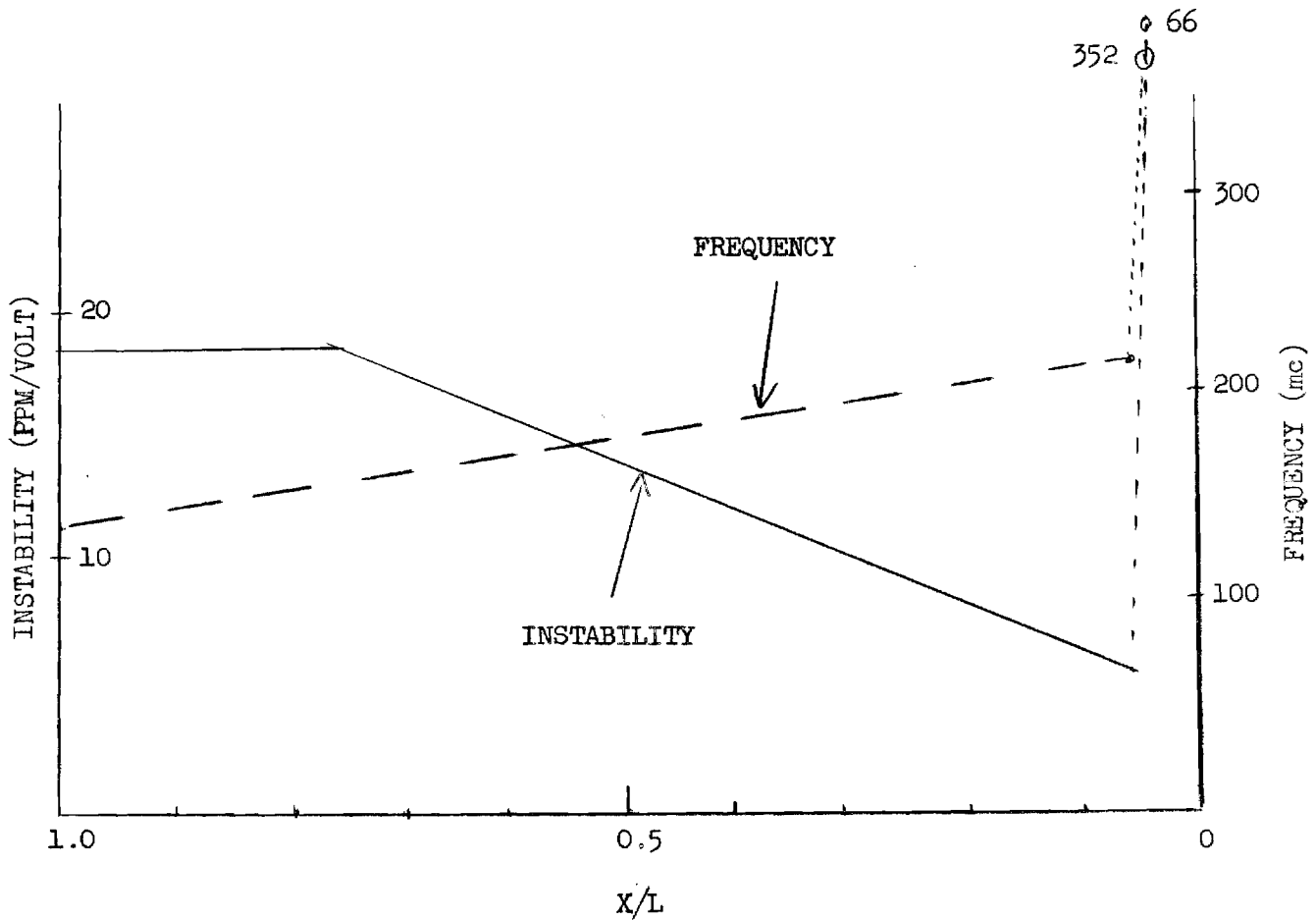


Figure 5.9. Tests on Open-Wire Line.

fastened in a strip secured across the open end. The plate pin and grid pin can now be connected by extremely short leads to their respective portions of the cavity.

This physical arrangement suffers from two disadvantages. First, the cavity cannot be hermetically sealed and, second, the stability will be considerably poorer than if connections were made at a low impedance point in the cavity. However, for some applications, particularly where a well stabilized voltage supply is utilized, the advantages of mechanical simplicity and the facility of obtaining cavity-controlled oscillations may outweigh the disadvantages named.

There will now be described a configuration which has been devised in an attempt to maintain the advantage of conductive coupling at the open end and at

the same time to minimize the disadvantages. The circuit arrangement is essentially that of the Clapp oscillator, in which a small capacitor is placed in series with the plate-to-grid inductance. The effect is to reduce the effective inductance of the frequency-determining element without materially affecting its Q . Improved stability compared to an equivalent circuit operating at the same frequency on a plate-to-grid inductance alone may be anticipated. This result may be inferred from the fact that in the latter circuit the value of inductive reactance required may be so small that the coil or cavity producing it may be of impractical size, while in the case of the series capacitor the size of condenser and coil (or cavity) may be selected for more nearly optimum results. Analytical considerations are summarized in the literature (8) and appear in detail in the original reference (9).

The conversion of the conductively coupled oscillator to an equivalent Clapp arrangement was not difficult, but the problem of how to produce an assembly which might in addition be hermetically sealed was less easily answered. It was finally decided to utilize a new uhf subminiature tube (RCA type 5718) mounted internally in the manner illustrated in Figure 5.10.

The subminiature tube is mounted inside the inner conductor, thereby permitting access of power leads by way of the electrically shielded central hollow region. The plate pin is connected by a very short lead to the hermetically sealed condenser which plays the part of the small series capacitor discussed above.

A few tests have been conducted on a 400-mc oscillator which utilized the latter configuration. The series capacitor was of the variable type and permitted a considerable tuning range (about 12 per cent) to be used. The instabilities resulting varied from less than one ppm/volt at the upper end of the frequency band to about three ppm/volt at the lower end. It is believed that this can be improved upon by more careful consideration of design parameters.

It is planned, during the next quarter, to conduct further investigations of comparable configurations, particularly with regard to means of combining the

requisite of stability-versus-voltage variations with that of stability-versus-temperature variations. It is expected that frequency bands up to 900 mc will be brought under observation.

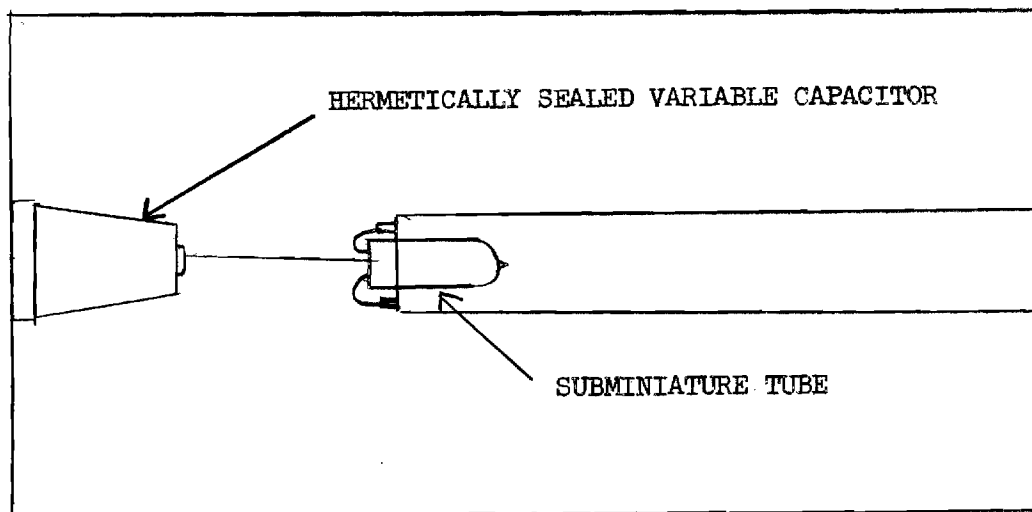


Figure 5.10. Cavity-Controlled Oscillator with Internally Mounted Tube.

C. Temperature-Compensated Cavity and Controlled Oscillator

In the previous report (2) it was shown that a temperature-compensated cavity had been constructed which exhibited instabilities of the order of one-half part per million per degree centigrade. It was decided to test the ability of this cavity to control the frequency of an oscillator under conditions of varying temperature but fixed voltage.

To conduct this test, it was first necessary to bring an oscillator under cavity control. This was established by placing the tube, a 6AF¹⁴, outside the cavity with the tube base close to the leads of a hermetic seal. The resultant coupling exhibits considerable leakage flux because of the necessary length of the external leads; hence, an instability of 1.5 ppm/volt was the best that could be achieved. This, though far from optimum, was deemed acceptable and permitted prosecution of the temperature test.

The whole oscillator assembly was now placed in a temperature-controlled chamber. The anode potential was kept constant at 150 volts throughout the tests. The results of the tests are shown in Figure 5.11 in which the effects of temperature cycling are shown. Tests were conducted on two successive days, as illustrated, and temperature excursions of over 70° C were utilized.

Encouragingly small frequency deviations resulted. This single test indicated that the cavity exercised primary control throughout, inasmuch as the frequency deviations were little different from those when the cavity alone was subjected to identical temperature cycling.

It is planned to conduct similar tests on the 600-mc cavities which were described in the previous chapter of this report. If equivalent data can be acquired on several oscillators, a better basis for predicting the effect of temperature on assembled units may result.

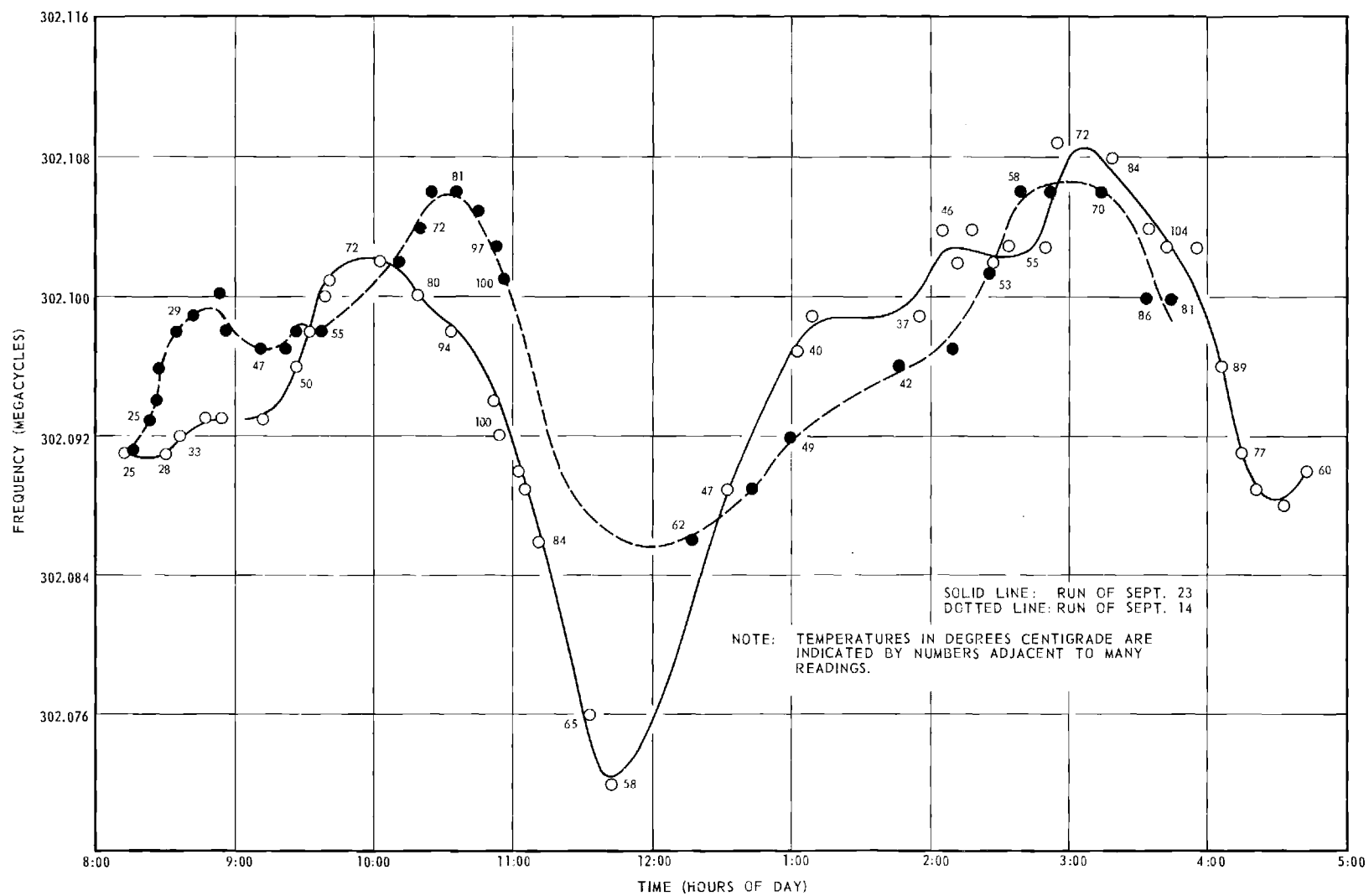


Figure 5.11. Frequency Variations of a Cavity-Controlled Oscillator.

VI. THE HIGH-ORDER OVERTONE RESPONSE OF QUARTZ CRYSTALS

The work on quartz crystals during the past quarter has been pursued along three lines. First, a study has been made of the responses of unmounted crystal blanks at high-order overtones. Second, a series of bridge measurements has been conducted on various circuits embodying crystals, with the hope that they would yield quantitative information concerning the changes produced in the amplitude and phase of the impedance of the circuits in question, at and near the crystal overtone response frequency. Third, the possibility of utilizing the principle of automatic frequency control, with a crystal as the controlling element, has been investigated. This last method involves the use of a discriminator circuit which, in the absence of the crystal, gives a d-c voltage output, the magnitude of which is determined by the frequency of the signal applied at the input of the discriminator. With the crystal in the circuit the discriminator curve of d-c voltage vs. applied frequency is modified in a decisive way at the overtone frequency of the crystal and gives promise of a feasible crystal-controlled oscillator at frequencies higher than those for which crystal control has heretofore been effective.

The oscillator, which has been described in a previous report (2), was used with very little modification to test the responses of some unmounted crystals supplied through the courtesy of the Signal Corps. The modification consisted of eliminating the coupling loop shown in Figure 6.1, page 39 of reference 1, and connecting the pickup electrodes directly across the fine-tuning capacitor. These electrodes were copper disks, approximately 5 mm in diameter, soldered to the ends of brass screws. The crystal was held at two points on its periphery, and the disks were spaced on either side of the crystal by amounts which could be varied by adjusting the screws. Figure 6.1 shows a sketch of this mounting.

With this arrangement responses were observed at frequencies throughout the tuning range of the oscillator. For instance, with a 5-mc blank, responses were observed at 207, 217, 227 and 237 mc, and with a 20-mc blank, responses at 222 and 262 mc were detected. However, all of these responses were very weak compared to those observed previously (2) with conventionally mounted crystals. Furthermore, the spacing of the electrodes seemed to have little

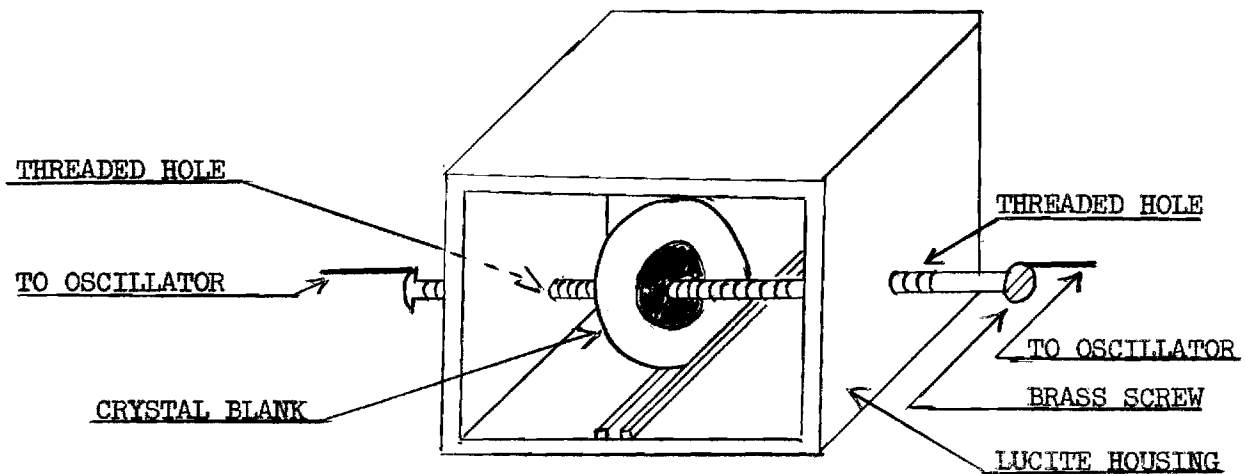


Figure 6.1. Crystal Mounting.

effect on the magnitude of the responses, provided that the coupling to the crystal was tight enough to yield any response.

In view of the disappointing results of this experiment it was decided to abandon this approach, at least for the time being, and concentrate for the most part on the mounted crystals which have consistently yielded large responses. One type of mounted crystal on which the above-described experiment will be repeated is one consisting of a blank, gold-plated over a small circular area on each side, with leads soldered directly to the plating. Perhaps the tighter coupling will be conducive to better responses (although, in light of the results just described, there is not much reason to expect this) while the shunt capacitance will be considerably less than for a conventional mounting.

This group has been of the opinion for some time that more quantitative information is needed concerning both the crystal parameters at the frequencies in question and the effect which these crystals have on the circuits in which they are employed. Unfortunately, the experimental difficulties encountered in a search for this type of information are great, principally because of the fact that measuring devices of the requisite stability are not readily available. During the recent conference between this group and Mr. Sykes, Dr.

Van Dyke, and Dr. Gerber, to which reference has been made in Chapter III of this report, Dr. Van Dyke stressed the importance of getting this type of information. Consequently a series of experiments was attempted in which use was made of a recently acquired Hewlett-Packard generator and impedance bridge covering the range from 10 to 500 mc.

A mounted crystal with a 5-mc fundamental was coupled to the transmission line oscillator by the conventional loop arrangement, and a very strong response was displayed on an oscilloscope. The signal from a TS-175/U frequency meter was superposed on the crystal response, and the frequency of this signal was measured with a Gertsch frequency meter. The overtone response frequency of the crystal was thus determined to be 277.41 mc. Next the power was removed from the oscillator, the terminals of the transmission line next to the tube were connected to the bridge, and the bridge was supplied with an r-f signal from the signal generator. The magnitude and phase of the impedance was measured throughout a band of frequencies centered about 277.41 mc.

It was hoped that at the resonant frequency a sudden change in the impedance would take place. No such sudden change was observed. The impedance varied in a perfectly regular manner throughout the frequency interval. In fact, the removal of the crystal from the circuit had no measurable effect on the impedance. This result, though negative, did yield two pieces of information: (a) the degree of coupling between the crystal and oscillator was small; and (b) the oscillator-detector is a very much more sensitive device than the bridge for detecting crystal resonances.

Next a suggestion made by Mr. Sykes was followed up. The crystal (B-5 AR No. 5) was coupled to a coaxial cavity by means of a loop. The crystal was known (2) to have a response at 297.5 mc, and the cavity was tuned by means of an adjustable lucite plug to this same frequency. The coupling loop was made large in order to accomplish two objectives. First, it gave tight coupling and, second, it broadened out the response of the cavity through loading. The latter condition was desirable because the effect of the crystal could be more easily found if it were superposed on a broad rather than a sharp cavity response. A diagram of the experimental arrangement is given in Figure 6.2.

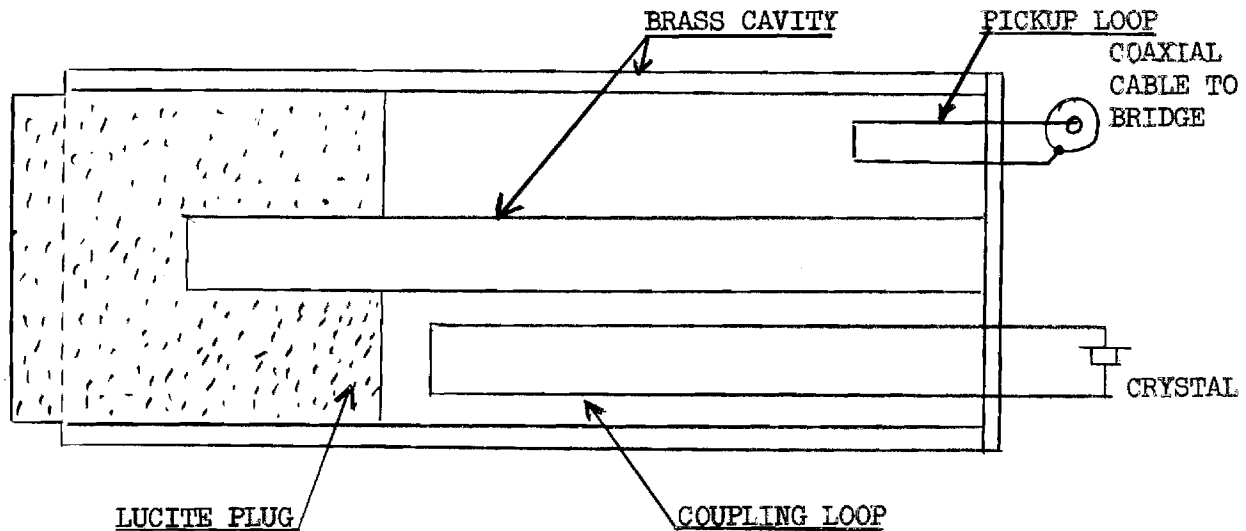


Figure 6.2. Crystal and Cavity.

A run consisted of measurements of the magnitude and phase of the impedance of a small pickup loop coupled inductively to the cavity as the frequency of the Hewlett-Packard generator was varied. Measurements were taken at frequencies approaching the center frequency of the cavity and yielded results typical of the cavity. However, when the center frequency, which was also the crystal overtone frequency, was reached, balance could no longer be obtained, and the object of the experiment was defeated.

Presumably the trouble was that the frequency of the generator was not sufficiently stable. As it drifted rapidly back and forth over the response of the crystal, the impedance of the pick-up loop was changed by so much, and so rapidly, that it could not be followed by the bridge.

In one test the crystal was connected to the bridge through a length of coaxial cable of known impedance, and the combined crystal and cable impedance was investigated as a function of frequency. The results were similar to those obtained for the combination of crystal and cavity: bridge balance could not be effected at resonance.

These experiments serve to point up the difficulty of obtaining the type of quantitative information desired with present equipment. They make manifest the need for measuring equipment, in this frequency range, suitable for use with high-Q devices such as crystals.

It was decided to investigate the possibility of adapting the method of automatic frequency control to the present problem. One conventional a.f.c. system uses a discriminator, the d-c output voltage of which is a function of the frequency applied to the input. The frequency-sensitive d-c output is used to control the frequency of the device supplying the signal to the discriminator. Therefore, a necessary condition for successful operation is that the frequency of the signal source be controllable by a suitably injected d-c voltage.

A circuit diagram of a conventional discriminator is given in Figure 6.3A. For details of operation reference 8 may be consulted. As the frequency of the input departs from f_0 , the center frequency of the secondary tuned circuit, the output voltage varies as shown in Figure 6.3B. Over the range from f_1 to f_2 the output voltage is an almost linear function of impressed frequency, and it is this region over which control is possible, providing the signal generator is frequency-sensitive to applied d-c voltage.

In the circuit just discussed, the ability to control frequency is determined by the slope of the linear portion of the response curve, which is in turn determined by the Q of the secondary. If a crystal were substituted for the capacitance, as illustrated in Figure 6.4, and if the secondary were tuned so that the resonant frequency of the coil and crystal holder capacitance coincided with the crystal resonance, it might be expected that the response of the discriminator would be extremely sharp because of the comparatively high Q of the crystal.

To test this possibility the circuit of Figure 6.4 was designed around a 5-mc crystal operating on its fundamental. The stage of amplification was necessary to raise the signal to a conveniently detectable level. A signal from an r-f generator was supplied to the input, and the d-c output measured as a function of input frequency at several points in the neighborhood of 5 mc. The resulting plot is presented in Figure 6.5 and shows quite clearly that the crystal determines the slope of the response curve at the crystal resonance

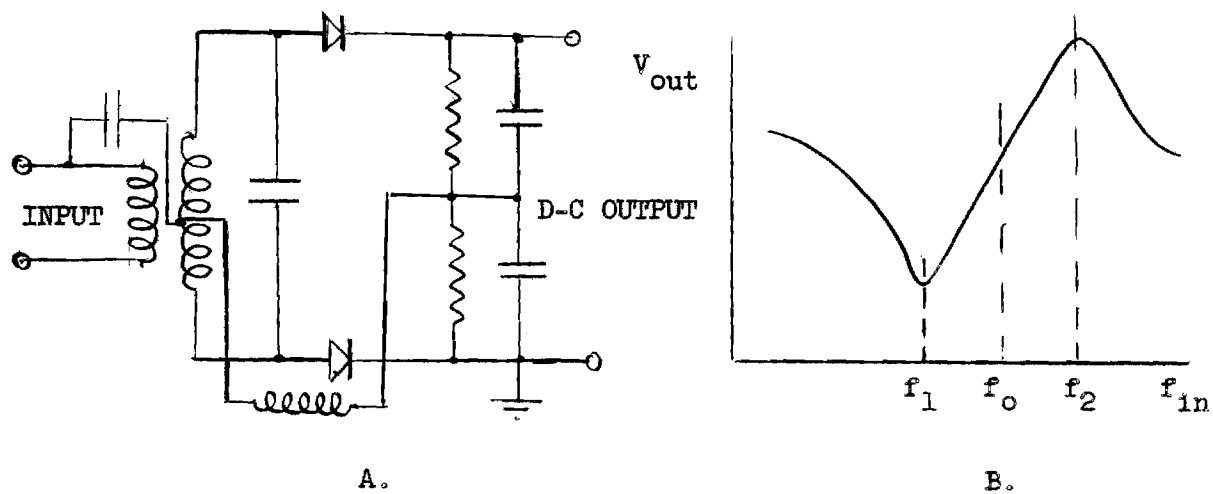


Figure 6.3. Conventional Discriminator Circuit and Response Curve.

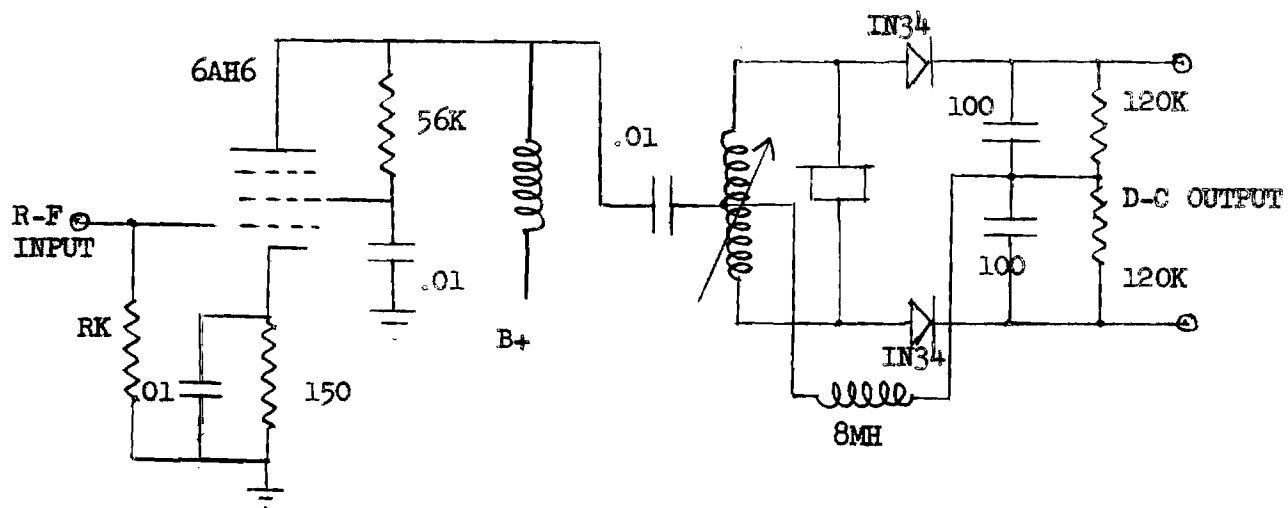


Figure 6.4. 5-Mc Amplifier and Crystal-Controlled Discriminator Circuit.

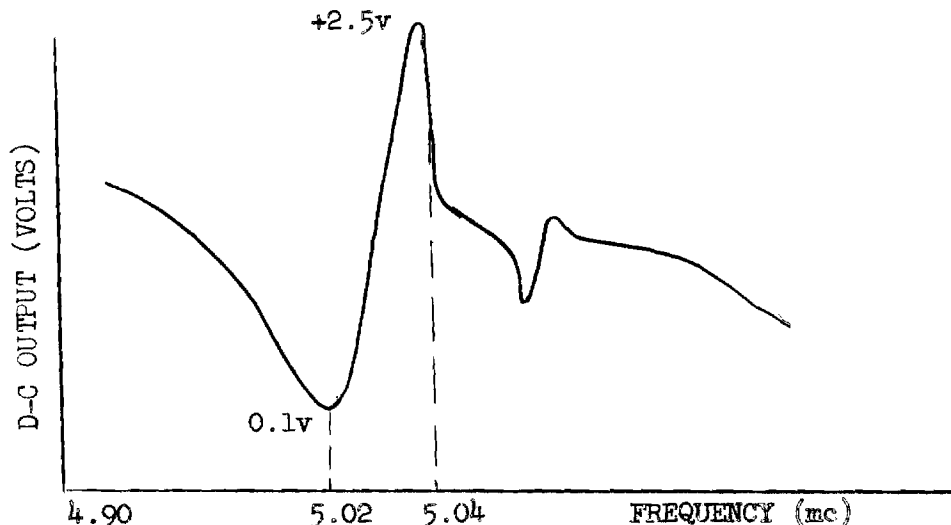


Figure 6.5. Response Curve of 5-Mc Crystal-Controlled Discriminator

frequency. The existence of a small spurious response will be noticed at a frequency somewhat above the crystal fundamental. The slope of the steep portion of the curve is approximately 0.15 volts/kc.

After the basic idea of the crystal-controlled discriminator had been proven to have some merit, it was decided to attempt to test the action at 25 mc, the fifth overtone of the crystal. Consequently, the circuit of Figure 6.4 was redesigned only to the extent of changing the transformer. When the response near 25 mc was measured, the plot of Figure 6.6 resulted. Very pronounced discriminator action was present, was present, in fact, at each of several spurious response frequencies. These spurious responses are a property of the particular crystal being used and of the particular overtone and should not be considered as a basis for serious objection to the method.

It was decided next to run a test at 175 mc, the 35th overtone of the 5-mc crystal. At this frequency great difficulty was encountered with the circuit of Figure 6.4, particularly with the transformer. The primary and secondary coils degenerated to portions of turns, and the problems of center tapping the secondary and getting the requisite coupling presented considerable difficulty.

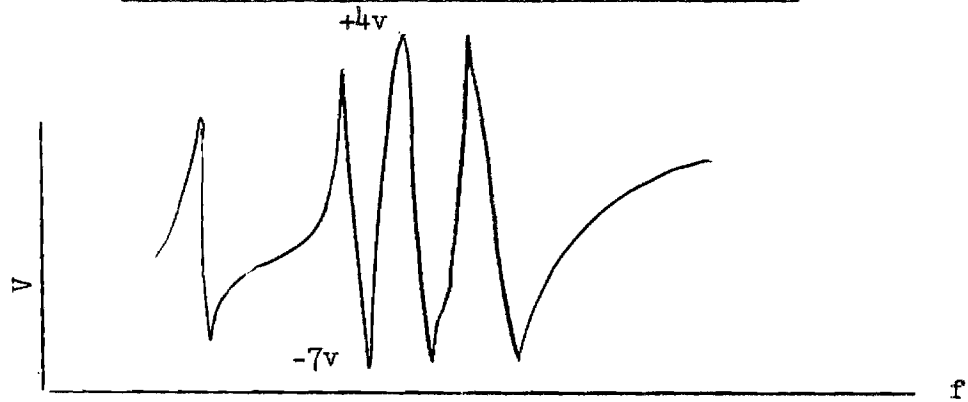


Figure 6.6. Response Curve of 25-Mc Crystal-Controlled Discriminator.

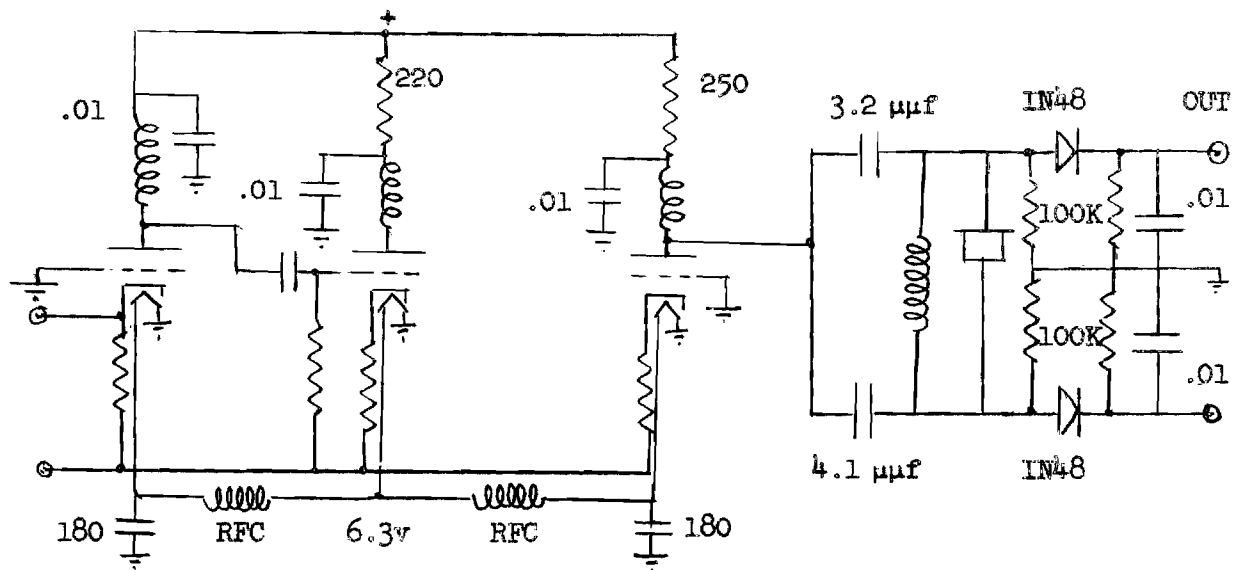


Figure 6.7. Amplifier and Direct-Coupled Discriminator Circuit.

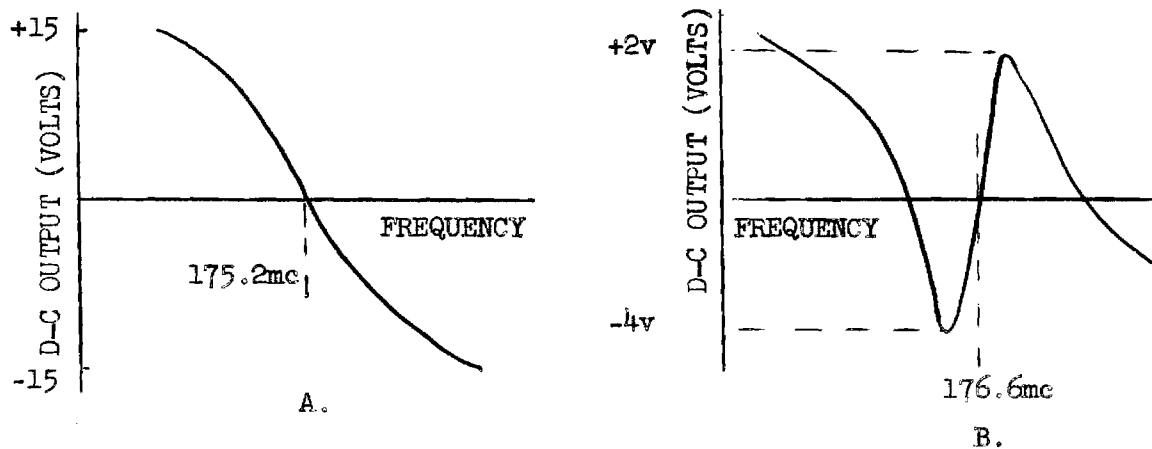


Figure 6.8. Direct-Coupled Discriminator Response Curve Near 175 Mc.

In fact, satisfactory results at this frequency were never obtained using transformer coupling. A redesign was carried out by Mr. J. C. Sellers, and the circuit of Figure 6.7 was constructed by him. The three stages of amplification shown were found to be desirable, and the particular form of the stages was largely determined from impedance considerations, the circuit being designed to operate from a Hewlett-Packard signal generator with an output impedance of 50 ohms. The coil of the discriminator was tuned, by a spreading of the turns, so that the resonant frequency of the coil and the crystal-holder capacitance coincided with the overtone response frequency of the crystal.

The direct-coupled discriminator response was investigated first with a capacitor in place of the crystal. The capacitance was chosen to be equal to that of the crystal holder. A plot of the response curve of this experimental arrangement is presented in Figure 6.8A. Next the crystal was inserted as shown in Figure 6.7 and another run taken. This yielded the plot of Figure 6.8B.

The shift in frequency for corresponding points of A and B is due to the fact that the dummy capacitance used for A was not exactly equal to the crystal holder capacitance, while the fact that the crystal response is not exactly symmetrical about the d-c-voltage-equals-zero axis may be accounted for by the lack of exactness in tuning the discriminator coil to the crystal overtone frequency.

There are many ways in which a d-c voltage may be made to control the frequency of an oscillator. From the standpoint of the present problem the simplest would be most desirable. The number of variable parameters must be kept a minimum, and this requires that the number of circuit elements, particularly tubes, be kept a minimum. Consequently, a test was made of one of the simplest possible methods, namely the effect of bias variation of a Clapp oscillator on its operating frequency. It was found that a change in the bias of one volt caused a change in the frequency of approximately 80 kc at the operating frequency of 177 mc. Since with the discriminator circuit just described a swing of one volt is obtained with a frequency change of only 8 kc, it would seem that good frequency control by this method is feasible. Other methods of using the d-c signal to produce the desired change in frequency will be considered, and the most satisfactory will be adopted.

One important requirement for a satisfactory discriminator is that the d-c output be a function only of the frequency and not of the amplitude of the applied signal. The effect of amplitude will be eliminated if the frequency of operation be chosen to coincide with the frequency at which the crystal-response portion of the discriminator curve cuts the axis.

VII. CONCLUSIONS

The attainment of a high order of frequency stability by means of coaxial cavities appears quite feasible when the principle of temperature compensation is applied to brass-Pyrex resonators. Further confirmation, however, awaits the completion of tests on three identical 600-mc resonators which have recently been constructed. The attainment of stability through the temperature insensitivity observed in certain ceramic materials appears, on the other hand, to be infeasible. Such ceramic materials have consistently failed to retain their silver-plated surfaces during assembly into finished resonators and thereby have lost their electrical conductivity.

Cavity control of oscillations can be achieved either by inductive coupling or by conductive coupling. The former method is quite satisfactory if the tube base is inside the cavity. However, when the tube is exterior to the cavity, the leakage inductance of the added leads reduces considerably the effectiveness of the cavity in attaining control of the frequency of oscillation and in maintaining satisfactory stability. Conductive coupling suffers the same ill effects of leakage inductance when the tube is exterior to the cavity. An arrangement in which the tube is mounted within the open end of the cavity and in which the conductive paths are completed by a small series capacitor permits the virtual elimination of leakage inductance. Reasonable, though not optimum, frequency stability may be expected from this configuration. Instabilities averaging 1.5 to 2 parts per million per volt change in anode potential were observed in a circuit of this type in the frequency band of 350-400-mc.

The tests which have been carried out on high-order overtone responses of quartz crystal resonators lead to the following conclusions:

1. Unmounted crystals yield unsatisfactory responses in the 200-300-mc region.
2. Measurements of crystal parameters at high-order overtones are impossible to make with the equipment presently available.
3. The behavior of quartz crystals in discriminator circuits offers hope that a crystal-controlled system in the 200-300-mc range is feasible.
4. Control of oscillator frequency by a suitably injected d-c voltage is possible. The best method for effecting this control has yet to be determined.

VIII. PROGRAM FOR THE NEXT QUARTER

The investigation of cavities will be continued. The three cavities designed to be substantially identical and to resonate in the 600-mc region will be subjected to extensive tests to observe the effects of temperature cycling upon long-term stability. The tunable cavity for the same range, now in the design stage, will be completed and tested. A further study of the possibilities of constructing satisfactory ceramic resonators will be made, and other materials such as fused quartz will be considered for utilization.

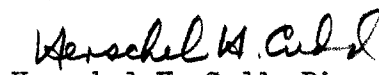
In the field of oscillators particular attention will be directed toward the conductively-coupled tunable cavity-controlled oscillator described in this report. Efforts will be directed toward construction of an oscillator of this type which will be insensitive both to changes of anode voltage and to variations of ambient temperature.

A preliminary investigation will be made of materials, methods and components applicable to the frequency range of one thousand to three thousand megacycles. Consideration will be given to means of stabilizing frequencies in this range. The studies involved will be utilized either as a basis of the report at the end of the quarter or for future experimental work, whichever is applicable.


The investigation of piezoelectric crystals will be continued. The behavior of two newly acquired units with high fundamental frequencies will be tested in the swept oscillator as well as in the discriminator. Methods of controlling frequency by the discriminator output will be studied, and an attempt to construct a complete crystal-controlled system at 188-mc will be made this quarter if time permits. As soon as possible the operating frequency of the discriminator will be increased to approximately 300-mc and crystal control will be attempted at this frequency.

Approved:


J. E. Boyd, Head
Physics Division


Herschel H. Cudd, Director
Engineering Experiment Station

Respectfully submitted,


Vernon Crawford
Project Director

IX. IDENTIFICATION OF KEY TECHNICIANS

This project is under the direction of Dr. Vernon Crawford who devotes approximately one-fourth time to this work. Dr. Crawford is Associate Professor of Physics; he received his Doctor's degree from the University of Virginia and specializes in electromagnetic phenomena. He worked on nuclear quadruple resonances in connection with station project 171-118, "Investigation of Frequency Control above 150 Mc."

Mr. Donald W. Fraser is serving as assistant project director. He is Assistant Professor of Electrical Engineering at Georgia Tech and holds the degree of Master of Science in Electrical Engineering from the same institution. He worked on station project 131-45, "High Frequency Crystal Controlled Oscillators," devoting approximately one-fourth time thereto. His other experience includes five years of electronic testing and research in the U.S. Navy. Mr. Fraser is currently devoting two-thirds time to this project.

Mr. James C. Sellers joined the project as Electronics Technician at its onset. He is currently devoting full time to the project. Mr. Sellers previously was engaged for eight years in nuclear instrumentation with the AEC at Oak Ridge, Tennessee, where he had extensive experience as a technician in design, assembly and testing of electronic circuits.

Mr. James C. Hogg, Jr., Assistant Research Professor, devotes approximately one-fourth time to this project. Mr. Hogg holds the degree of Master of Science in Electrical Engineering from the Georgia Institute of Technology. Mr. Hogg has had extensive experience in circuit design and oscillators both in the industrial and the research field. He was employed on a full-time basis on the S.C.E.L. projects "High Frequency Crystal Controlled Oscillator Circuits" and "Investigation of Frequency Control above 150 Mc."

Progress Report No. 3, Project No. 229-198

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ENGINEERING EXPERIMENT STATION
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PROGRESS REPORT NO. 4

PROJECT NO. 229-198

PRECISION FREQUENCY CONTROL TECHNIQUES
(500 mc and Higher)

By

DONALD W. FRASER

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CONTRACT NO. DA-36-039-sc-42590

DEPARTMENT OF THE ARMY PROJECT: 3-99-11-022

SIGNAL CORPS PROJECT: 33-142B

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NOVEMBER 1, 1953, TO FEBRUARY 1, 1954

PLACED BY THE U. S. ARMY
SIGNAL CORPS ENGINEERING LABORATORIES
FORT MONMOUTH, NEW JERSEY

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I. PURPOSE

The purpose of this project is threefold: (a) to continue work on stabilization of oscillators between 500 and 3,000 mc, using cavity resonators, (b) to continue work on frequency control utilizing high-order overtones of quartz-crystal blanks and (c) to undertake any other investigations which may arise during the course of the work outlined in (a) and (b) above, or which may be mutually agreed upon between the Contractor and the Contracting Officer or his representative.

By agreement with the sponsor, investigations of resonances below 500 mc may be prosecuted as preliminary steps in determining the feasibility of frequency control by the phenomena under study. In addition, cavity resonators previously under construction and designed to provide control of frequencies below 500 mc may be completed and tested as aids in perfecting measurement techniques which will later be applied to the range of frequencies above 500 mc.

II. ABSTRACT

There have been four objectives emphasized during the period of this report. Measurements to determine the characteristics of 600-mc coaxial-cavity resonators have been conducted, theoretical and experimental attention has been devoted to a series-tuned cavity-controlled oscillator, consideration has been given to a method of automatic frequency control utilizing the high-order overtone response of a quartz crystal and some time has been directed toward a literature study of novel means of frequency control.

The three 600-mc cavities completed during the previous quarter have been subjected to careful scrutiny. One has proved to be satisfactory in all respects, showing a satisfactory Q and demonstrating a temperature sensitivity no greater than one part per million per degree centigrade. The other two resonators have failed to retain a high Q after several weeks of storage and have been disassembled for inspection. The Q degradation resulted from a loss of silvered surface on the inner conductor at the pressure points of contact fingers. New tests are to be initiated using an Invar or fused-quartz center conductor.

A cavity-controlled oscillator consisting of an internally-mounted tube and a small series capacitor is undergoing theoretical and experimental study. It is believed that an optimum method exists for the selection of three controllable parameters, cavity length, cavity characteristic impedance and series-capacitive reactance, and that a proper choice can be determined to insure maximum frequency stability. Several assemblies have been constructed as means for establishing data.

Some attention has been given to the automatic frequency-control problem. A reactance-tube control circuit has been constructed and tested at 185 mc in an effort to use the high-order (37th) overtone of a 5-mc quartz crystal as a frequency reference in AFC. Partial but not satisfactory control has been achieved.

A limited literature search brought up several novel methods of frequency control in the lower UHF region. Consideration is being given to a possible extension of frequency range and to construction of a resonator out of low temperature-coefficient materials such as Invar and fused quartz.

III. CONFERENCES

During the month of December the project laboratory at the Georgia Institute of Technology was visited by Mr. Gonzales, a representative of the Squier Signal Laboratory. Although Mr. Gonzales' visit was primarily in conjunction with other Signal Corps contracts, he spent considerable time with personnel of this activity and was able to gain considerable information relative to both present engagement and future plans of this project. Some clarification of aims and viewpoints of the Contracting Agency resulted from the conference and will serve as an aid in outlining the scope of experimental work to be conducted during the coming year.

IV. COAXIAL-CAVITY RESONATORS

One of the primary objectives of this project has been the design and assembly of coaxial-cavity resonators which are quite insensitive to variations of ambient temperatures. The last report submitted (1) described resonators suitable for the frequency region centered at 600 mc which were designed to provide temperature insensitivity. This insensitivity was to be achieved by a compensation process similar to the one already successfully employed at lower frequencies. Three essentially identical resonators were constructed to provide vehicles for comparative tests on both a short-term and a long-term basis. In addition, work had been started on a tunable cavity which utilizes the same principles of compensation and which was designed to be tuned over a moderate frequency range centered approximately at 600 mc.

Previous tests have been conducted at 300 mc using a cavity Q-meter as the testing device. In this device two signal sources are employed; the most important is a frequency-modulated oscillator whose output provides the variable-frequency input to the cavity. The frequency-modulation required was introduced by the capacity variations in a vibrating condenser which was shunted between plate and grid of a Colpitts-type oscillator. This arrangement was described in detail in an earlier report (2). No difficulty was encountered in the 300-mc range in establishing completely stable operation; consequently, the desired tests were conducted expeditiously, and the results were not subject to significant errors.

The shift of frequency range upward to 600 mc resulted in serious difficulties in achieving satisfactory test procedures. It was first found that it was impossible to operate the oscillator at 600 mc and still retain the vibrating capacitor as a shunt element between tube electrodes. After the attempted utilization and subsequent abandonment of other similar configurations, an arrangement was adopted which has given satisfactory performance. The physical employment of the units is illustrated in Figure 4.1.

Upon eventual completion of a satisfactory oscillator, tests were initiated on the three 600-mc cavities. The results of presently completed tests upon one of the cavities are given in the following paragraphs. The other two were not tested for reasons which are explained therein.

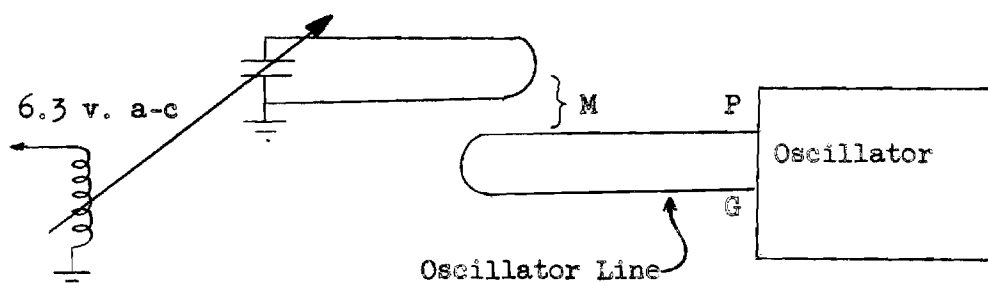


Figure 4.1. Arrangement Providing Frequency Modulation in a 600-mc Oscillator.

A. The 600-mc Compensated Brass Resonators

Although tests of the cavities were initiated early in the period of this report, the difficulties commented upon rendered data subject to doubt. The final establishment of stable oscillations and well-defined frequency modulation has permitted the compilation of information which is now considered factual and subject to little error, within limits of significance which are to be defined.

Figures 4.2 and 4.3 show the results of five test runs conducted recently on one of the three cavities. In each case a period of about three hours was involved, the upward cycle usually requiring about one hour and the downward cycle about two hours. It will be noted, and should be emphasized, that frequency deviations are referred to the frequency existing at the beginning of the run and not to an established or standard frequency of the cavity. In fact, the absolute resonant frequency of the cavity, at a prescribed temperature, showed an apparent change from day to day. The term "apparent" is used because the cavity Q-meter technique is essentially a comparative process and is not designed to give accurate absolute measurements. Other tests, such as operation of the cavity as the frequency-determining element of an oscillator, are required to establish more precisely long-term variations of the resonant frequency of the cavity.

An examination of Figures 4.2 and 4.3 show that the frequency deviation was in most cases considerably less than one part per million per degree

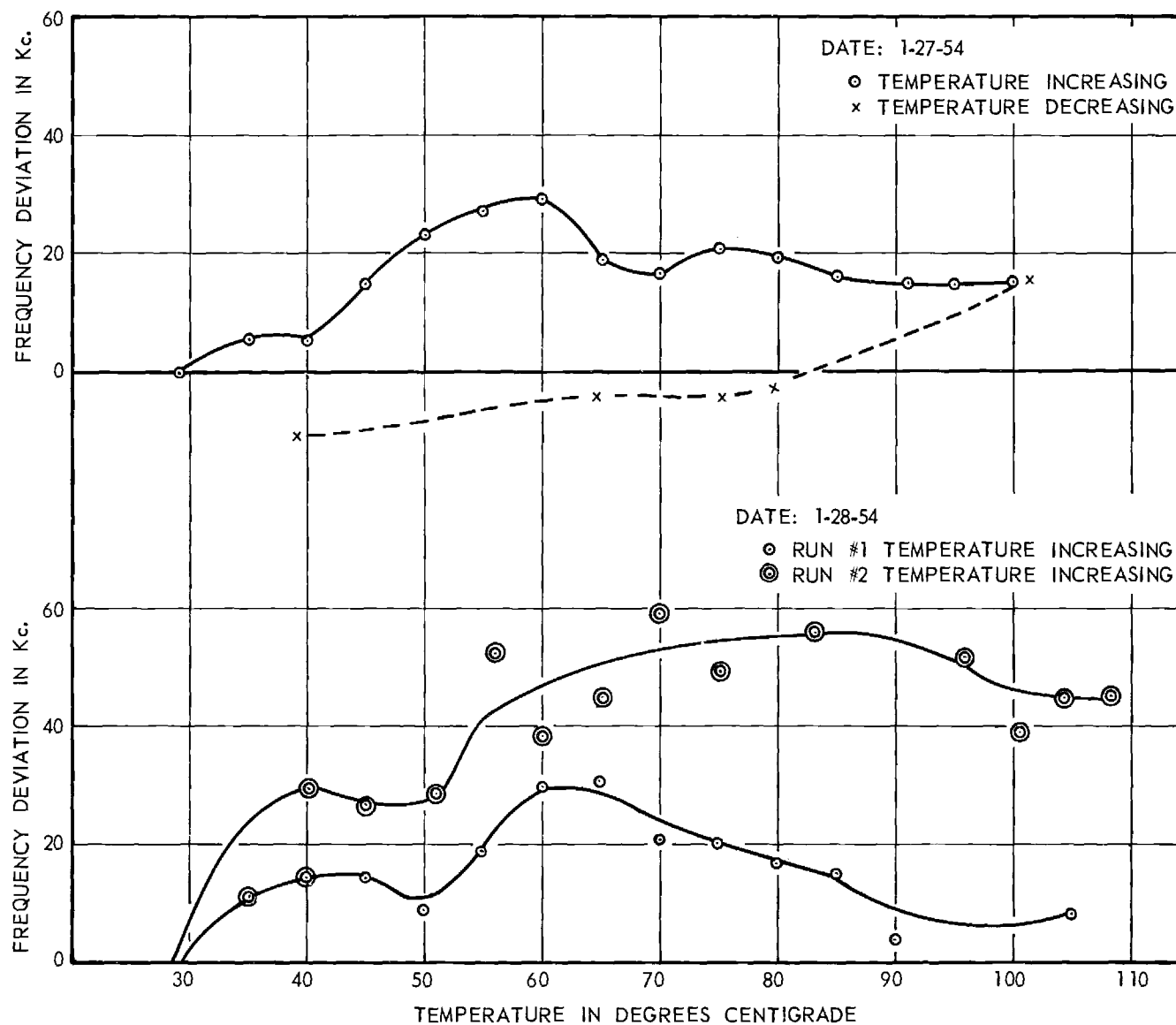


Figure 4.2. Frequency-Temperature Characteristic of a Compensated 600-mc Brass Cavity.

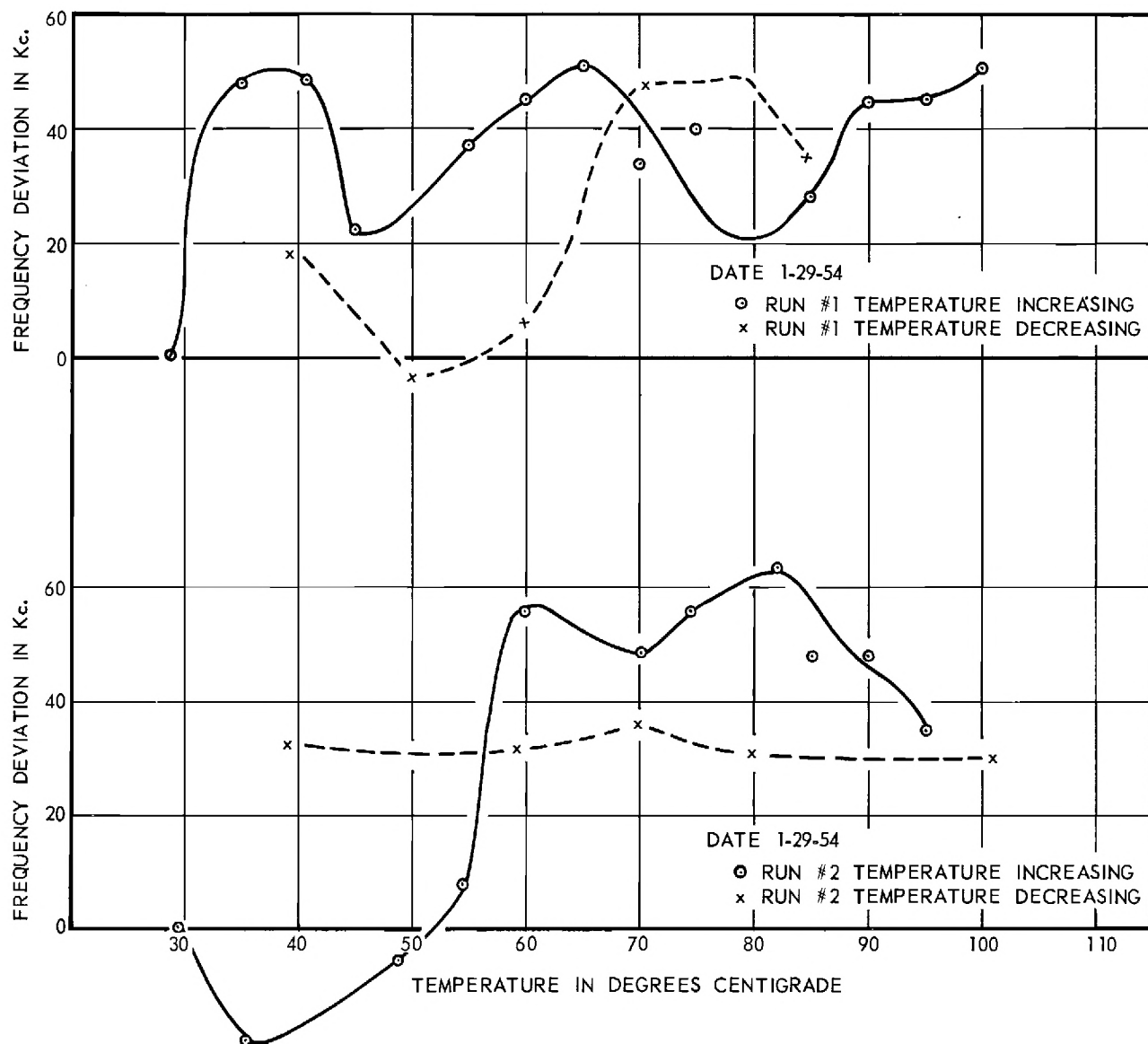


Figure 4.3. Frequency-Temperature Characteristic of a Compensated 600-mc Brass Cavity.

centigrade (ppm/°C), since at 600 mc one ppm/°C totaled over 70° is 42 kilocycles. Although the temperature sensitivity is somewhat greater than for the 300-mc resonator, it is better than any achieved in earlier tests using low temperature-coefficient materials without compensation.

The data cited refer to one cavity only. Although three such cavities were constructed, no tests were conducted on the other two. The planned and actually initiated series of tests on these two was terminated when it was discovered that the Q of each of the resonators was reduced to approximately one-half of the value measured at completion of assembly. This change occurred within an eight-week period and had no obvious explanation.

The two cavities were disassembled and all elements of the resonator were examined in detail. An explanation of the observed Q degradation was received when microscopic examination revealed a serious loss of silvered contact surface at points on the inner conductor. Records of this condition were obtained by photographing the affected areas. Enlarged views are shown in Figure 4.4. The scored surface represents a portion of the surface lying beneath the contact fingers which establish electrical continuity between the inner and the outer conductor. The deeper score actually portrays a condition where bare glass shows through the inner layer of fired-on silver.

It is evident that such loss of conducting surface invalidates whatever other advantages may be gained from the type of construction employed in these resonators. The possibility that certain impurities were picked up on the finger contacts used in these two resonators must be considered in light of the fact that the third resonator has shown no deterioration. The use of silver-plated glass-center conductors should not be considered impractical because of these failures pending further study of the effects of contact pressure on the surface. However, the limited time available on this project dictates that attention should be directed at this time toward other materials. These are discussed in the next paragraph.

B. Low-Expansion Materials for Resonators

An earlier report (2) discussed the use of the ceramic Stupalith as a basic material for cavity construction. It was concluded finally that the

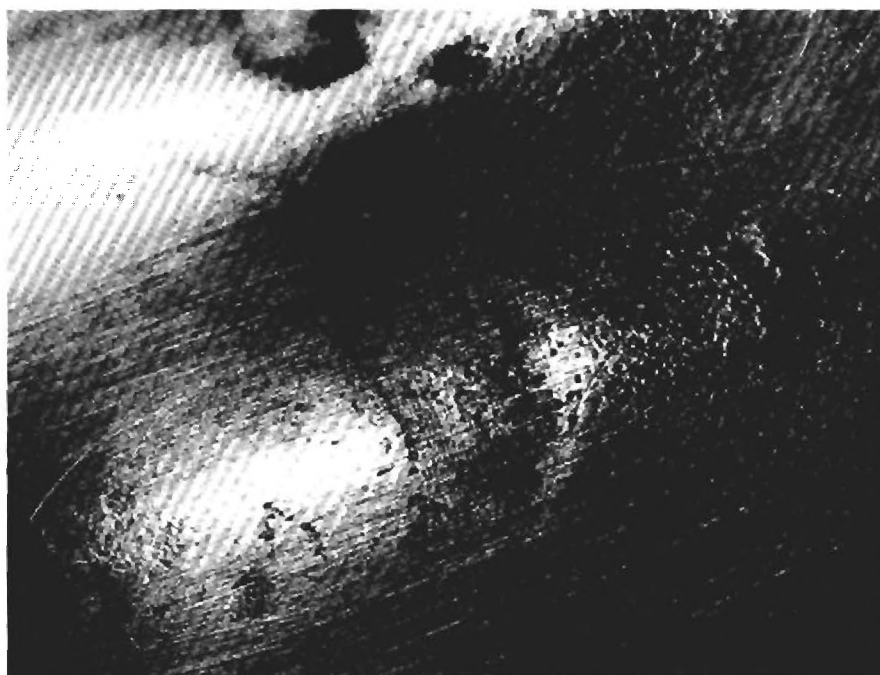
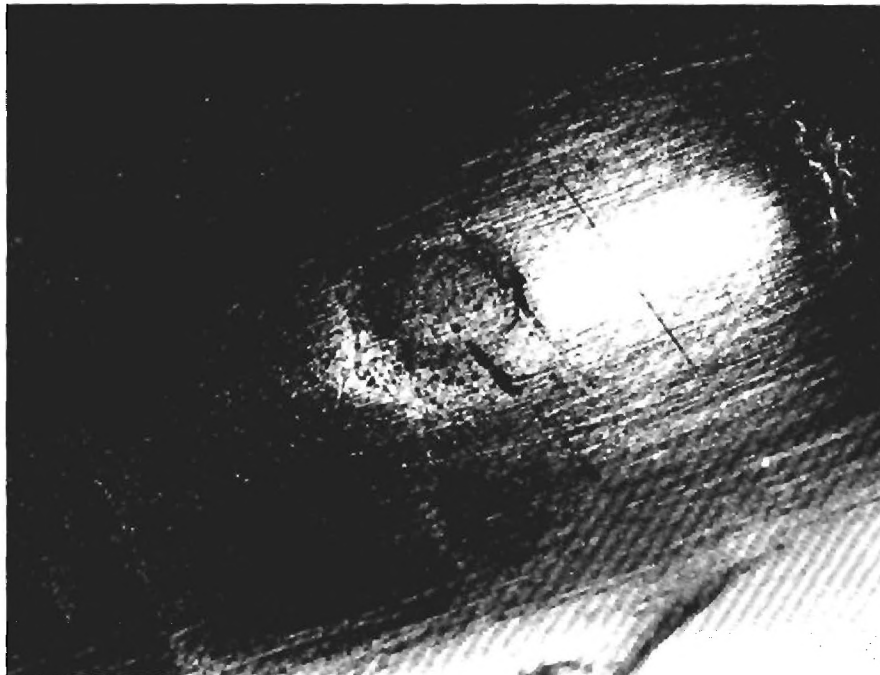


Figure 4.4. Photographs Showing Loss of Silvered Surface of Inner Conductor.
Magnified 11 times.

marked tendency of the material to lose its silver-plated surface rendered it unsatisfactory for resonator use. Mention was also made at the same time of two other materials which had attractive features. These were fused quartz and Invar, 30 per cent nickel-steel.

At that time it had not been possible to complete arrangements for acquisition of either of these materials. Within recent weeks, however, a manufacturer of fused quartz has agreed to fabricate coaxial cavities to our specifications. These will serve as convenient models for testing temperature characteristics and retention of silvered surfaces. In the case of Invar, it has not been possible to obtain tubing of the size required for resonator work. It is possible, however, to obtain rods of Carpenter Free Cut Invar in which the addition of a fraction of one per cent of selenium has made the material relatively easy to machine. Present plans are to attempt producing coaxial resonators by machining material from the interior of a rod of 2-1/2-inch diameter, leaving a portion about the axis intact to form the center conductor of the resonator.

The acquisition of 1/2-inch Invar rod will permit the re-evaluation of the compensated brass resonators discussed in the preceding paragraphs. By reducing the length of the compensating section, the coefficient of expansion of Invar can be accounted for.

Tests of all the items mentioned will be conducted and reported on as early as practicable after receipt of the material.

V. A SERIES-TUNED CAVITY-CONTROLLED OSCILLATOR

In Progress Report No. 3 (1) some brief comment was made relative to a cavity-controlled oscillator which contained a small internal series-capacitor as a tuning element. Since that time considerable thought has been given to the methods of construction of such an oscillator in a manner to make use of the series capacitor both as a tuning control and as a frequency-stabilization member. Such utilization has been suggested by Mr. Pritchard of the Squier Laboratories; some similar ideas have been published by Pettit (3).

The assembly of a resonant circuit employing a coaxial cavity and a small variable capacitor in series with its center conductor offers several parameters for which an optimum combination exists. These parameters include the reactance of the capacitor, the characteristic impedance of the cavity and the length of the cavity. In the following paragraphs these factors and their application to the problem of obtaining optimum frequency stability are discussed.

A. Theory of Series-Tuned Cavity

The basic circuit of the oscillator is seen in Figure 5.1.

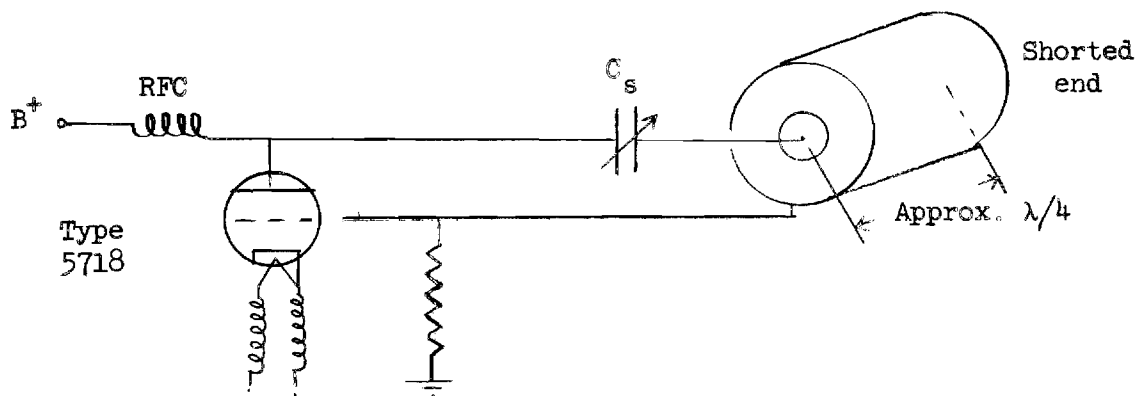


Figure 5.1. Oscillator Schematic.

The tube was actually mounted in the center conductor of the coaxial cavity, as shown in the accompanying photograph and Figure 5.2.

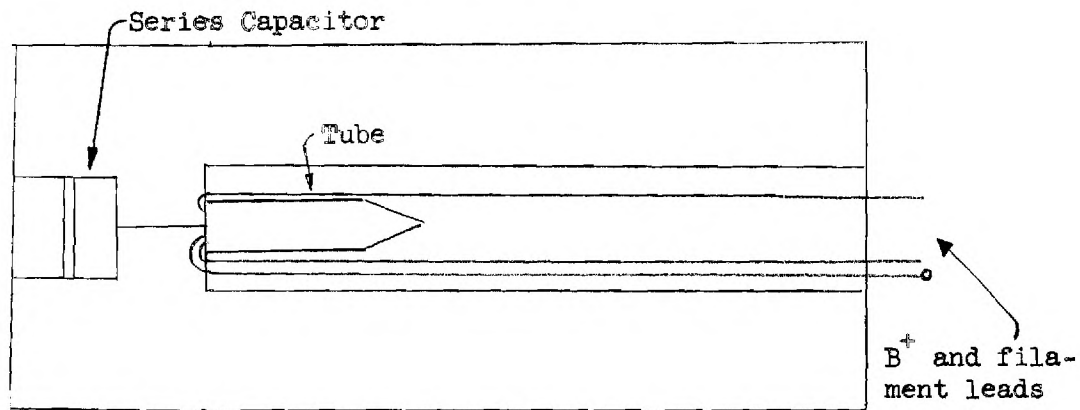


Figure 5.2. Circuit Mounting.

From this figure the adaptability of this oscillator to hermetic sealing as well as adequate shielding can be seen.

The equivalent circuit of the oscillator follows in Figure 5.3.

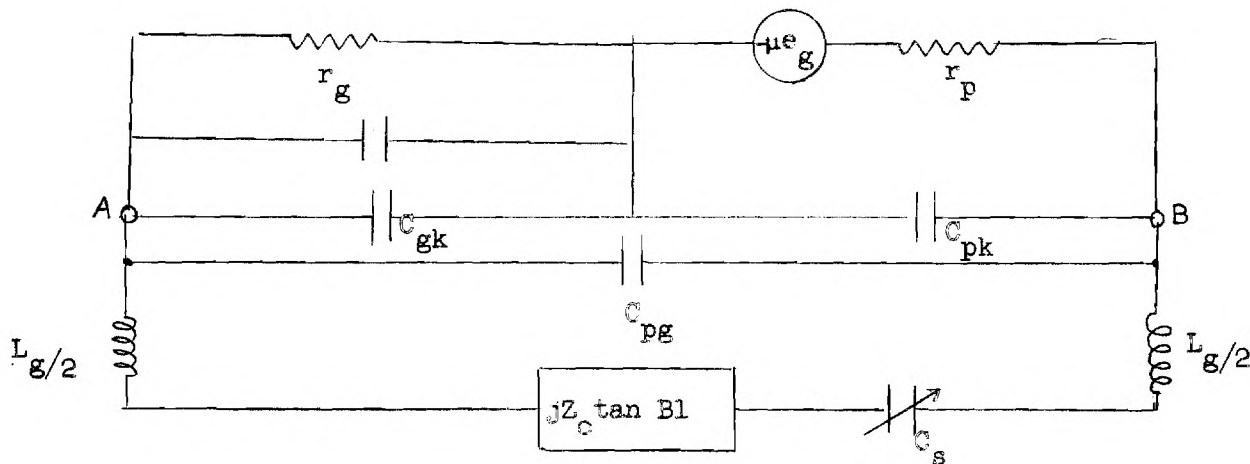


Figure 5.3. Equivalent Circuit of Oscillator.

Looking toward the tube at the terminals A-B, one finds essentially a capacitive circuit of greater reactance than that caused by the lead inductance at the resonant frequency of this circuit. By providing added capacitance in series with C_s , the quantity $jZ_c \tan B l$ can be made large at the operating frequency; consequently, the cavity will be closer to its quarter-wave theoretical resonance point.

The quantity $[\tan Bl = \tan \frac{\omega l}{v}]$ will be a larger and more rapidly varying number as $\frac{\omega l}{2}$ approaches $\frac{\pi}{2}$. The magnitude of the inductive reactance, however, is limited by the Q of the cavity. Furthermore, if the cavity were to operate exactly in resonance, the inductive reactance needed could not be obtained.

The problem then resolves itself into obtaining the proper choice of Z_0 , C_s and l (the cavity length for any particular frequency). Some analytical work has been started to see if these parameters can be judiciously chosen for optimum frequency stability for any one particular tube type and frequency.

B. Experimental Work and Observation

Experimental work thus far indicates some interesting possibilities. Fixed values of Z_0 and l were used while C_s was changed, and the reactance was measured. In the accompanying curves of Figure 5.4 it is seen that for fixed parameters Z_0 and l , a small value of C_s , corresponding to the higher frequencies, gives a higher reactance change and thereby greater stability. The negative of the tube reactance is plotted to show the intersections with the $[\frac{j}{\omega C_s} + j Z_0 \tan Bl]$ reactance lines.

It can be seen by reference to Figure 5.5 that by lowering Z_0 one can operate nearer the cavity's resonant point with a smaller C_s and obtain a greater reactance change for a given frequency shift. Work is being planned to pursue this objective from both experimental and analytical points of view.

Figure 5.5 shows the comparative plot of two cavities of the same resonant length but different characteristic impedances. A plot of the cavity reactance alone is represented by the curve Z_1 , while that of the sum of the cavity and the series capacitor C_s is represented by the curve, $[Z_1 + Z_{C_s}]$. Oscillations are obtained at a frequency corresponding to point A. If the cavity characteristic impedance is lowered, a curve such as Z_2 is obtained. With the series C_s , $[Z_2 + Z_{C_s}]$ is seen to intersect the tube reactance curve at point B. A smaller value of C_s may be needed to provide an intersection at a point more favorable to frequency stability. The curve $[Z_2 + X_{C_s}]$ shows a more favorable crossing of the negative tube reactance line; that is, a small change in reactance presented by the tube will produce a smaller change in frequency at B than at A. The point A, however, represents a lower frequency. The same argument

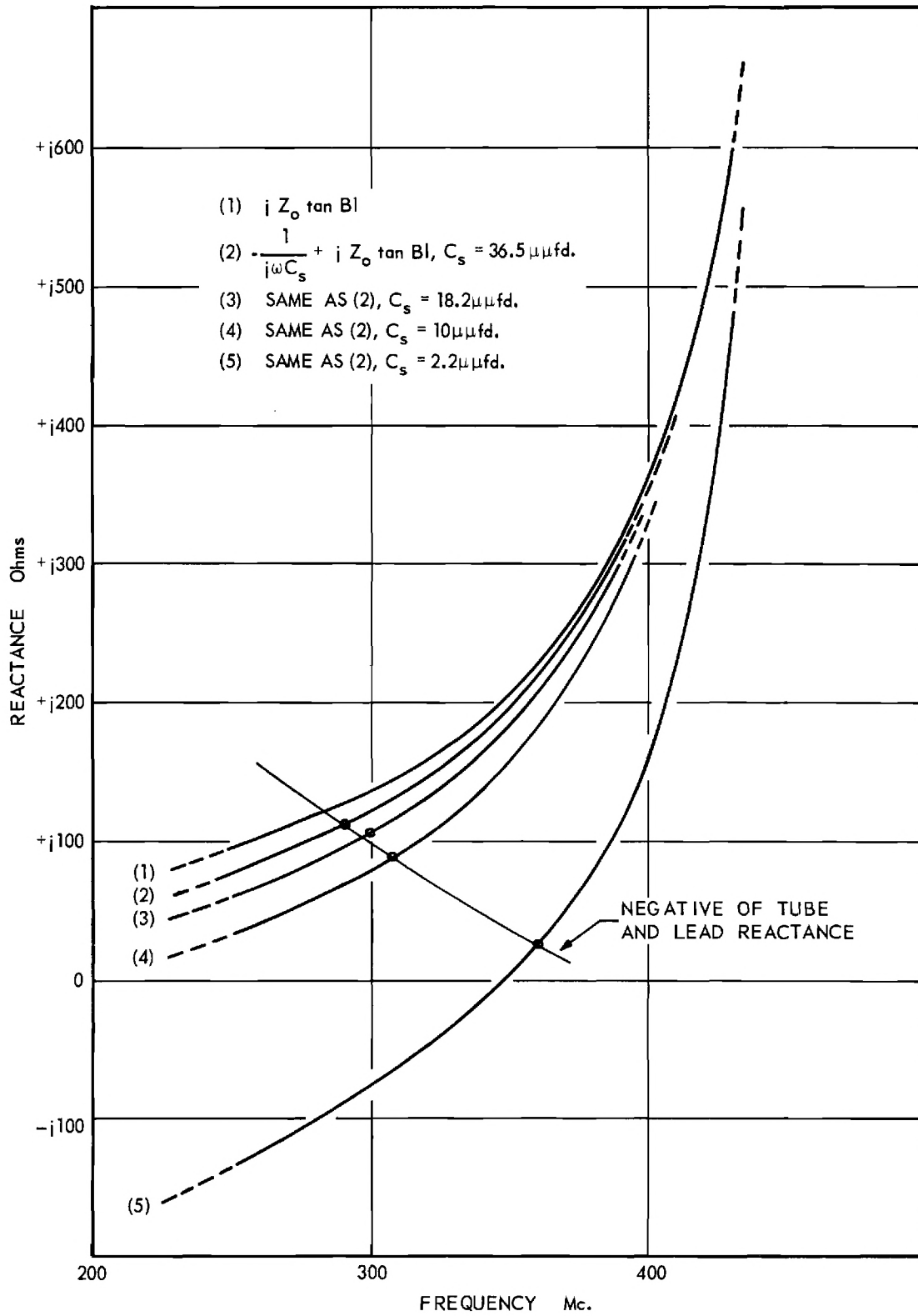


Figure 5.4. Reactance of Oscillator Elements.

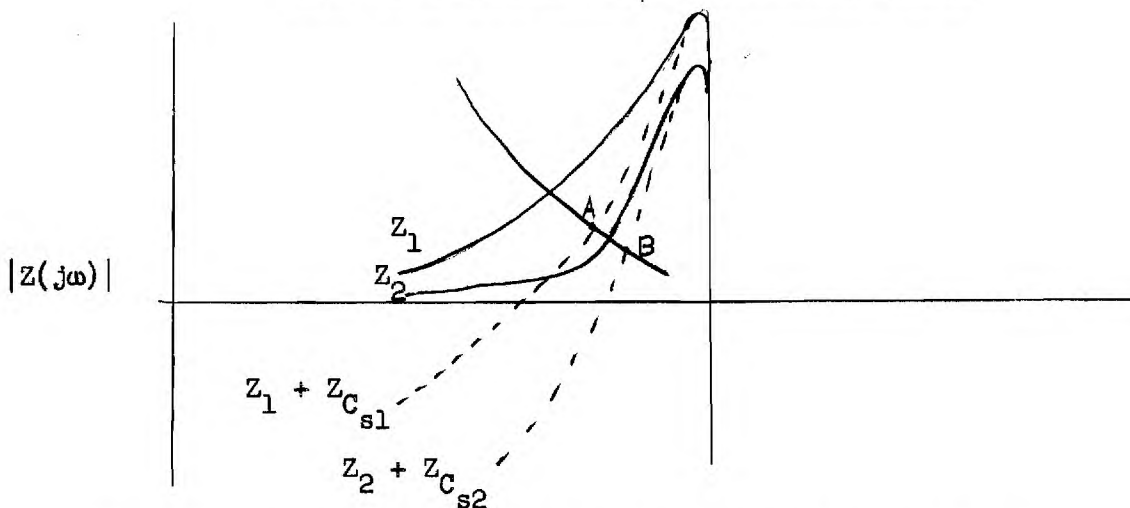


Figure 5.5. Effect of Varying the Cavity Characteristic Impedance.

may be presented in the case of a low Z_0 . At point A it would be necessary to make the cavity shorter and, hence, move the curves of Z_2 and $[Z_2 + Z_{Cs2}]$ to the left to obtain an intersection at point A rather than B. This means that greater stability is obtained when the cavity is operating near resonance. However, the frequency of cavity resonance may not be closely approached for the reasons previously stated.

These arguments conclude, then, that for operation over a band of frequencies with a given cavity length, operation must be carried on well below the cavity resonant frequency. In this region the problem of choice of parameters seems to be somewhat different. Referring to Figure 5.6 it can be seen that the curve of $[Z_1 + Z_{Cs1}]$, corresponding to a higher Z_0 than $[Z_2 + Z_{Cs2}]$, crosses the tube reactance curve at an angle more nearly approaching the vertical. This would indicate that the higher Z_0 tends to give better stability when the operating point is far removed from the resonant frequency of the cavity.

A test cavity with oscillator was constructed for the purpose of determining some of the effects of varied parameters upon frequency range and upon tuning. Photographs of the configuration are shown in Figures 5.6 and 5.7 and illustrate the present mechanical arrangements. The physical size of the present cavity is somewhat larger than is contemplated for working models but provides a convenient vehicle for present tests.

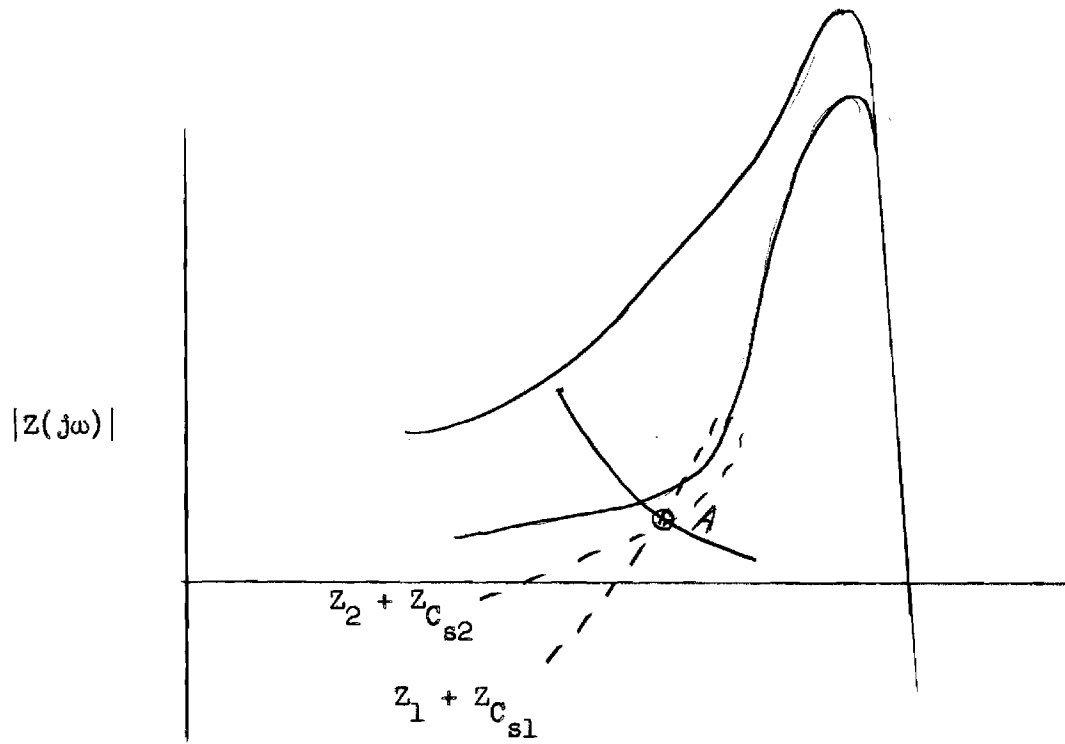


Figure 5.6. Effect of Varying the Cavity Characteristic Impedance.

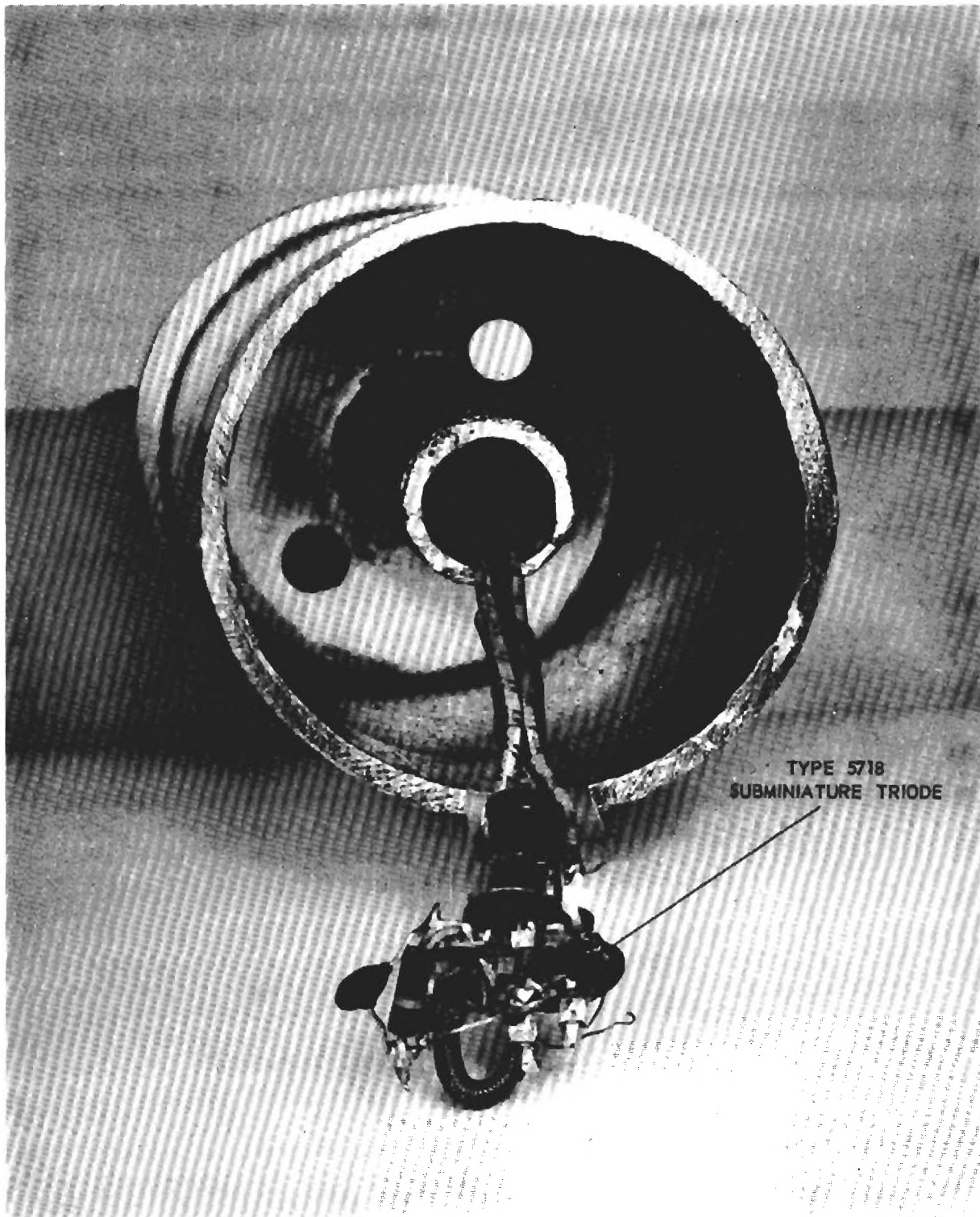


Figure 5.7. Oscillator Assembly Removed from Cavity.

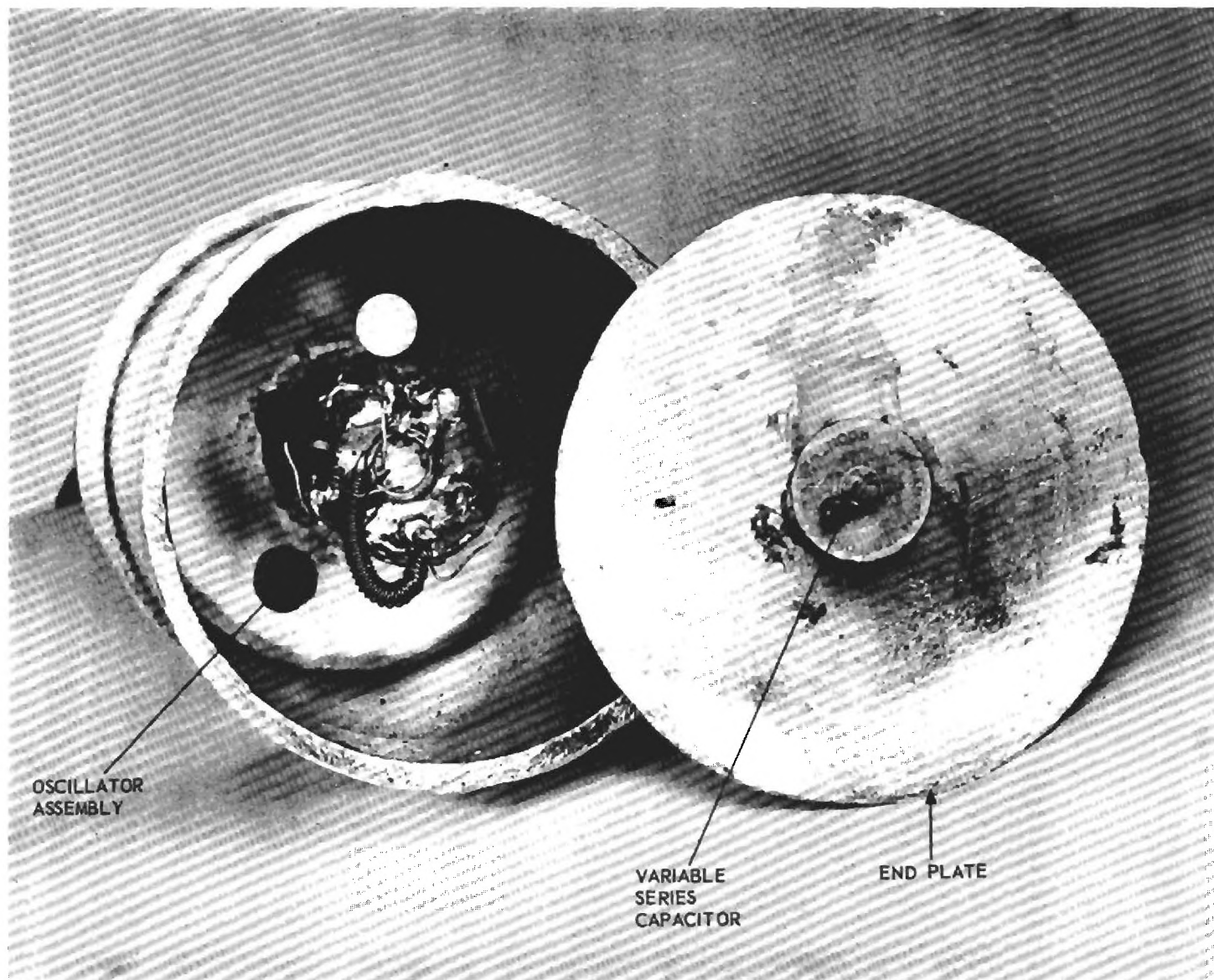


Figure 5.8. Oscillator in Position in Center Conductor.

VI. APPLICATION OF HIGH-ORDER OVERTONE RESPONSES OF QUARTZ CRYSTALS

The work on quartz crystals, as described in a previous report, embodied a study along three major lines. First, the responses of unmounted crystal blanks to high-order overtones were obtained. Second, bridge measurements on various circuits containing crystals were made to gain quantitative information concerning the changes produced in the amplitude and phase of the impedance of the circuits in question, at or near the crystal overtone response frequency. Third, the possibility of utilizing the principle of automatic frequency control, with a crystal as the controlling element, was considered. This last item involved the use of a discriminator circuit, which, in the absence of the crystal, gave a d-c voltage output, the magnitude of which is determined by the frequency of the signal applied at the output of the discriminator. With the crystal in the circuit, the discriminator curve of d-c voltage versus applied frequency is modified in a decisive way at the overtone frequency of the crystal and gives promise of a crystal-controlled oscillator at frequencies higher than those for which crystal control has heretofore been effective.

This third method has been initially investigated for possible use with a reactance-tube circuit as the closing loop factor for automatic frequency control of the oscillator. The crystal-discriminator output voltage is utilized as the correcting- or controlling-error voltage.

A. AFC at VHF and UHF with Reactance Tubes

In applying reactance tube action to VHF and UHF oscillators, care must first be exercised in the selection of the proper type tube for the reactance agent, since the interelectrode capacitance of nonminiature type vacuum tubes will immediately disqualify their use. For this reason, a common-grid type reactance circuit, using a miniature-type tube, was selected.

A look at the governing features of this type circuit will help to give a composite picture of the minimum requirements necessary to produce reactance action. The basic circuit of a common-grid reactance tube is shown in Figure 6.1.

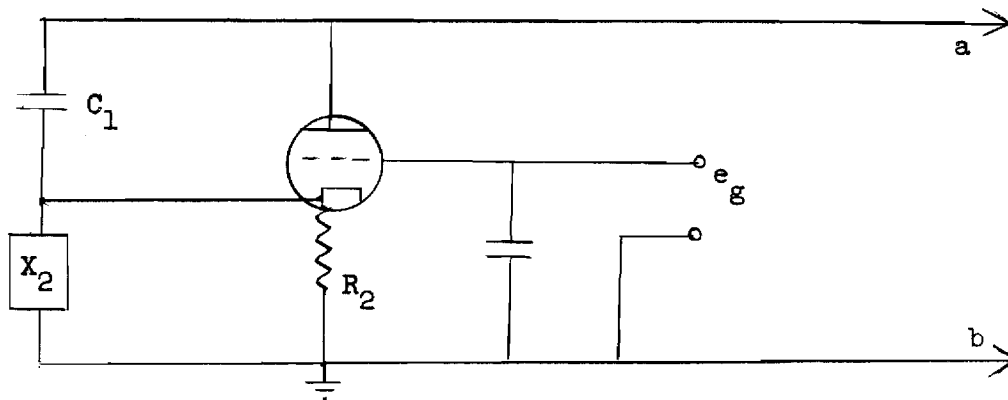


Figure 6.1. Common-Grid Reactance Tube Circuit.

It can be shown (4) that circuit conditions can be adjusted so that equivalent parallel reactance and resistive components between terminals ab are

$$X_{ab} \approx X_1(1 + R_2 G_m)$$

and

$$R_{ab} = \mu R_2$$

so that the oscillator tank circuit is in parallel with a capacitance, C' :

$$C' = \frac{C_1}{1 + R_2 G_m}.$$

The reactive component depends upon the mutual conductance of the tube and can be made a function of bias and discrimination (modulation) voltages applied to the grid circuit. If the amplification factor of the tube remains constant, the resistance component is independent of tube operating conditions, and loading on the oscillator is uniform.

The difficulty of obtaining a precise knowledge of component values at VHF and UHF makes circuit equations difficult to apply to circuit design. In order to achieve peak or proper circuit performance, it was necessary to make changes and adjustments under operating conditions.

Using a type 6AF4 miniature triode, it was necessary to change the basic common-grid design to the configuration shown in Figure 6.2.

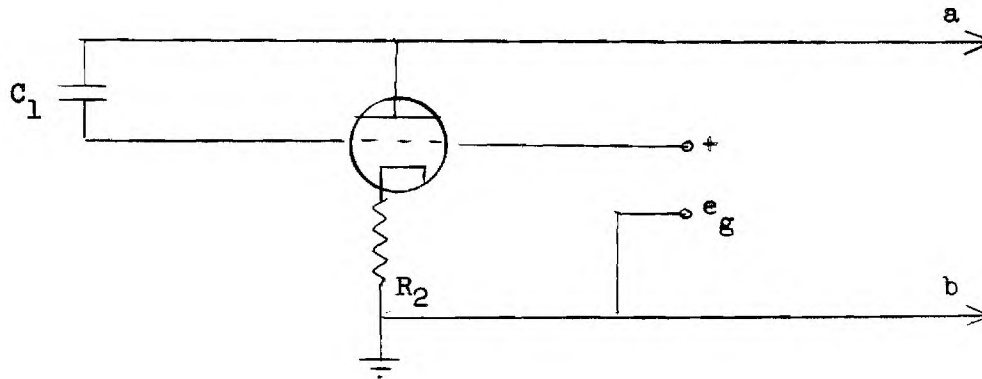


Figure 6.2. Modified Common-Grid Circuit.

Applying circuit theory, it was found that the equivalent parallel capacitance between terminals ab was $C' = C_1 R_2 G_m$, where R_2 = the total resistance in the grid-cathode circuit. When a bias or modulating voltage is impressed across the terminals of the grid circuit, it will vary the grid voltage of the tube and clearly vary G_m . A variation in mutual conductance will change the effective capacitance, C' .

Since the end results of a plate current flowing out of phase with the applied r-f plate voltage is obtained with this practical change using the type 6AF4 tube, it was planned to be used as part of the proposed automatic frequency-control loop.

B. Tests and Results

To test the variation in effective capacitance of the reactance tube, in terms of oscillator frequency change, a varying (low impedance) d-c potential was applied to the grid circuit of the 6AF4, resulting in the data given in Figure 6.3. Figure 6.4 shows the oscillator and reactance tube circuits used in the test. The linearity indicated in the grid-voltage frequency curve, Figure 6.3, of approximately 0.16 mc/volt, showed promises of having significant corrective action when energized by the proper magnitude and polarity by the discriminating voltage.

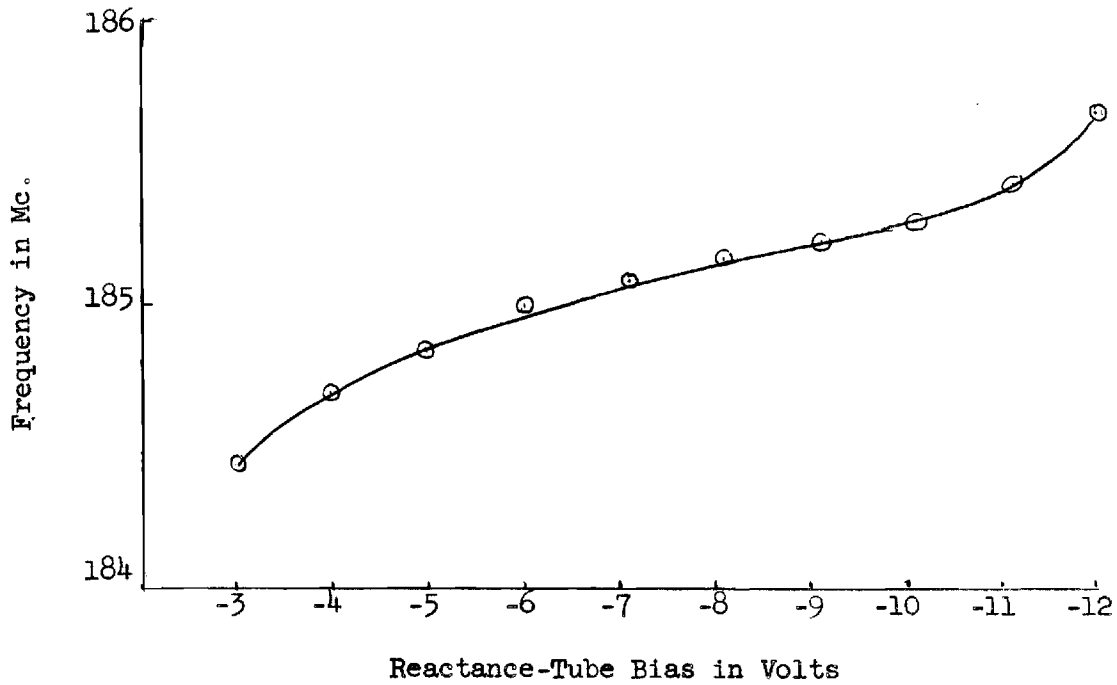


Figure 6.3. Change in Oscillator Frequency as a Function of Reactance-Tube Bias.

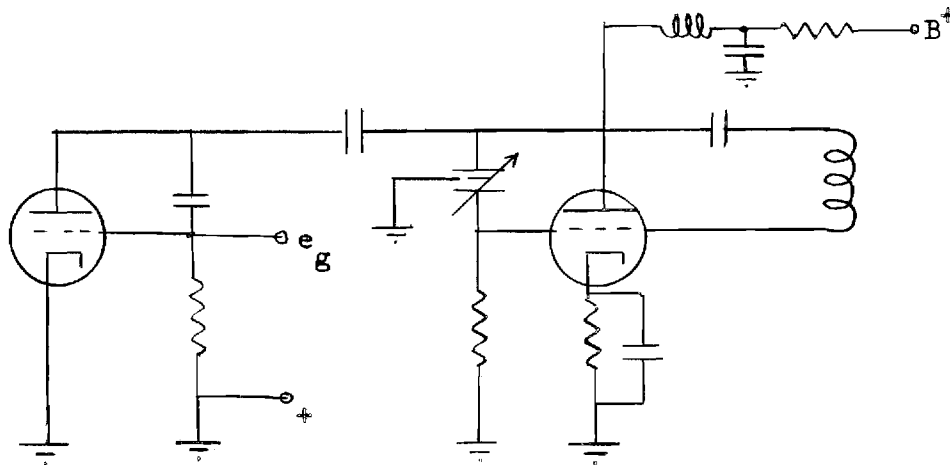


Figure 6.4. Oscillator and Reactance Tube.

The discriminator used in the tests (shown in Figure 6.5) was of the transformerless type designed by Mr. J. C. Sellers of this project, and was first investigated with a capacitor in place of the crystal. Only one change was made in the discriminator circuit, the variable capacitor replaced a fixed-type capacitor which enables a more rapid adjustment of the desired voltage magnitude.

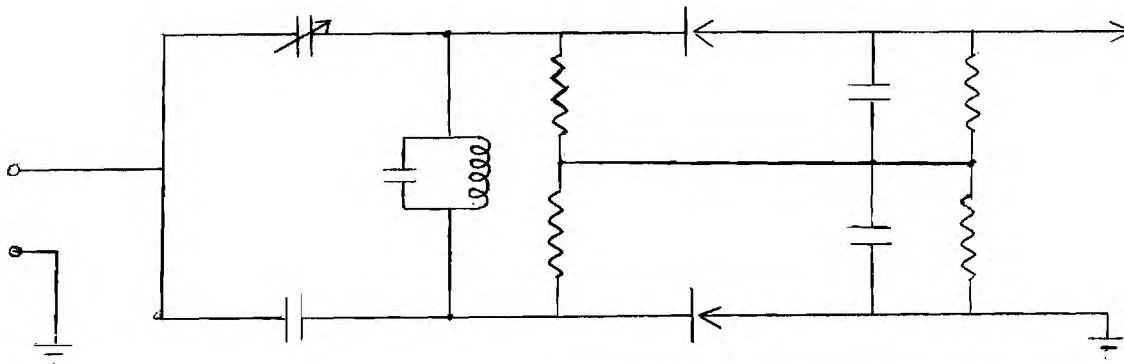


Figure 6.5. Discriminator Circuit.

In order to grasp a composite picture of the discriminator, reactance tube and oscillator in action together, a third test was made to observe oscillator-frequency change as a result of discriminator and reactance-tube action. The oscillator was of the conventional design used in a previous project test, a Colpitts type oscillator using a 6AF4 type tube. The following arrangement was set up. A Hewlett-Packard signal generator, varying about the center frequency, f_0 , was fed into the discriminator. The resulting discriminator output voltage, a function of frequency, was further fed into the grid circuit of the reactance tube via a cathode-follower circuit for isolation purposes thereby altering the value of the tuning capacitance in the main oscillator. A plot of these variable readings is shown in Figure 6.6.

Analysis of these curves indicated that the voltage output of the discriminator was not operating the reactance tube sufficiently for effective capacitance variation. An average of 70 kc/volt occurred at the reactive tube for a 700-kc change originating at the discriminator.

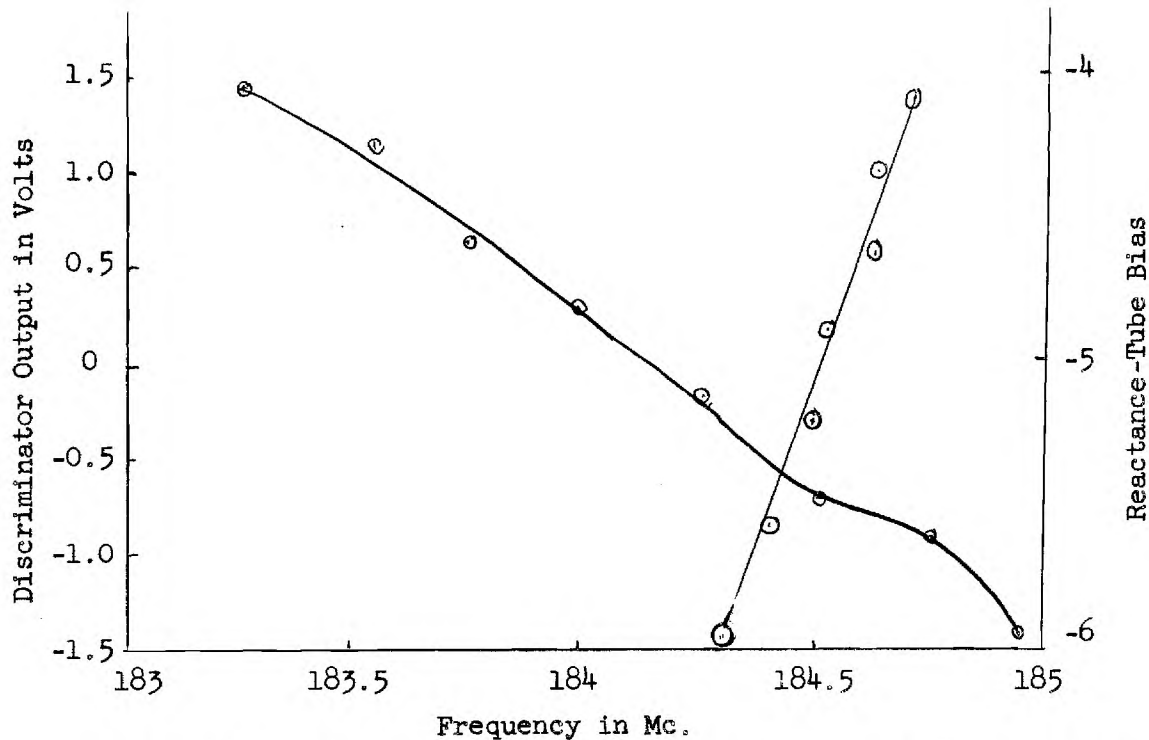


Figure 6.6. Composite Action of Discriminator and Reactance Tube.

With ample reactance-tube information a number of runs were made with the capacitance and crystal alternately replaced in the discriminator circuit. The oscillator, with the reactance tube attached, was operated at a fixed grid voltage and served as the signal generating source for these runs. Considerable difficulty was encountered in the oscillator-discriminator coupling loop in attempting to increase the discriminator d-c output voltage for inconsistent frequency regions. Poor oscillator action was suspected but the situation was remedied by decreasing the coupling between oscillator and discriminator loops. Resulting curves from these tests using capacitance and crystals in the discriminator tuning circuit are shown in Figure 6.7 A and Figure 6.7 B respectively.

The voltage magnitude of the crystal response at its 37th overtone was in the order of 1.3 volts swing, accounting for a frequency change of roughly 45 kc, or approximately 0.0288 volt/kc. In an attempt to increase the voltage variation, a high-frequency auto transformer was wound and placed in the coupling

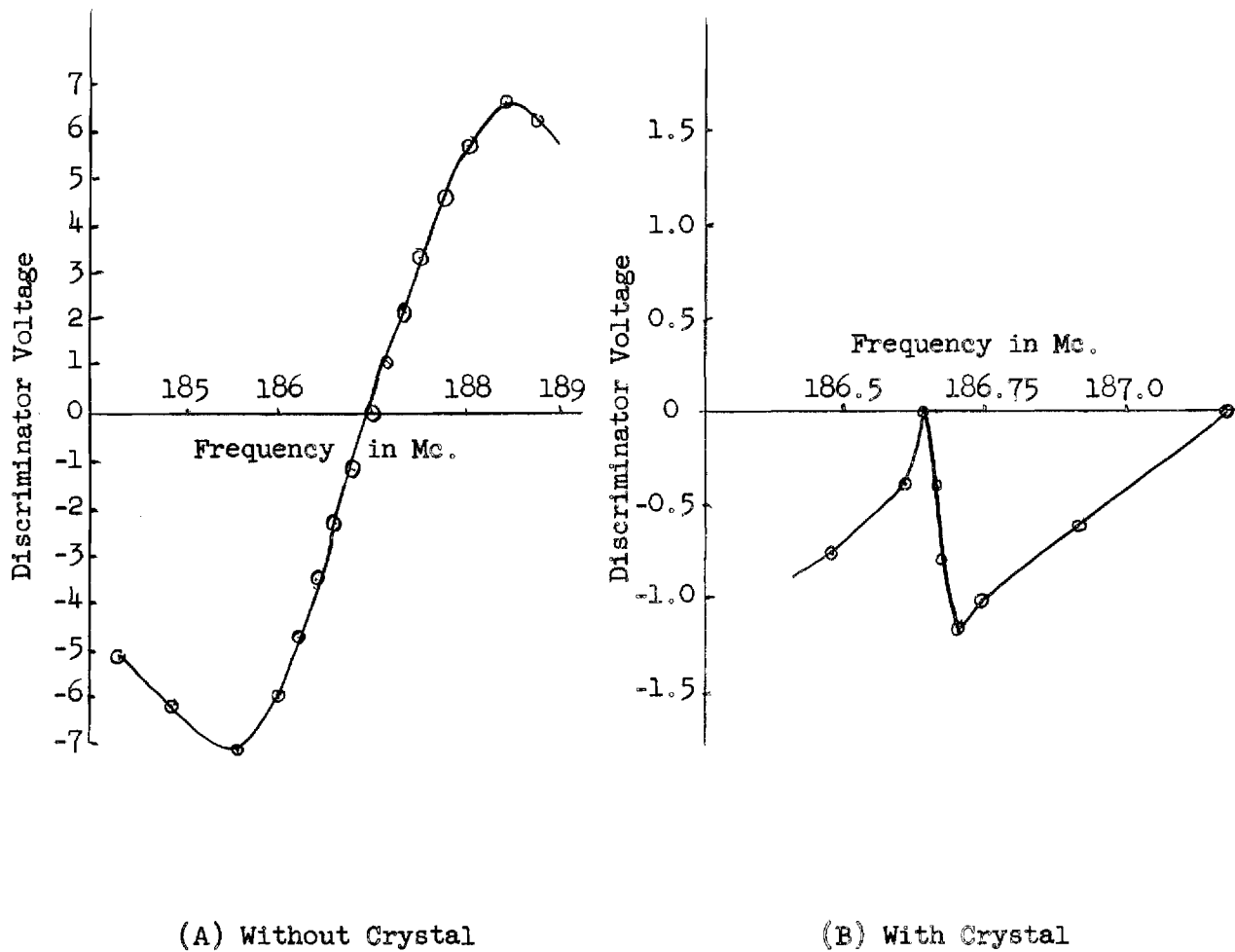


Figure 6.7. Discriminator Curves.

circuit of the oscillator and discriminator. This increased the voltage swing by a factor of approximately 0.6.

The basic idea of the crystal-controlled discriminator feeding a connection voltage to a common-grid reactance tube has proven to have merit. The use of a d-c amplifier placed between the discriminator and cathode follower for greater d-c variation to the reactance-grid circuit is contemplated.

VII. VARIOUS METHODS OF FREQUENCY CONTROL AT UHF

One of the primary objectives of this project, as stated in section I of this report, is to achieve stabilization of oscillators in the 500- to 3,000-mc region by utilization of cavity resonators. The same section further states that consideration shall be given to other methods of achieving frequency control within the same band of frequencies. Although the term "frequency control" is not specifically defined as to context, it has been presumed to signify the generation of discrete frequencies, each having a relatively high order of stability. Two criteria of stability have been adopted: the first relates to temperature sensitivity and the second relates to the effects of other parameters. The frequency deviation due to temperature variations is a directly measurable quantity; on the other hand, the frequency changes caused by those variations in circuit parameters which are not attributable to temperature effects must be judged by arbitrary standards. A convenient standard and one which is commonly employed is defined in terms of the frequency deviation caused by a discrete change of plate voltage in the frequency generator under investigation.

In this project each of the individual problems of stability have been separately attacked. To date, minimization of temperature sensitivity has been achieved by means of compensating sections in coaxial resonators. Encouraging results have been obtained at 300 mc and satisfactory results are indicated at 600 mc. However, at higher frequencies more severe mechanical tolerances will be required in the size and spacing of the compensating sections; hence, it has been deemed advisable to investigate other means of achieving temperature insensitivity. It has been noted in section IV of this report that two materials, fused quartz and Invar, may be satisfactorily utilized in the construction of cavity resonators with slight temperature sensitivity. Their capabilities are to be investigated.

The problem of stability as a function of variation of other parameters has been discussed in previous reports of this project. It is known that the presence of a high Q in the frequency-determining element, the minimization of leakage inductance and the adoption of proper coupling techniques all contribute to high orders of frequency stability. These factors have been considered in

detail in the oscillators which have been constructed to date, but it has not been evident that all, or nearly all, of the possible coupling and control methods have been considered.

A decision was made to conduct a brief literature search to unearth means of frequency control which have been investigated by other activities with the possible end of applying the principles to the specific objectives of this project. This search was conducted recently and, although there is no present assurance that any of the methods described can be directly or indirectly utilized, it is felt that the investigation has been of value in giving assurance that no presently known method of achieving frequency control at UHF has been overlooked.

It is believed that a compilation of these various means is of value in a report of this type. Therefore, the following paragraphs contain a brief summary of the descriptions and uses of several frequency-control devices which have been utilized in portions of the 500- to 3,000-mc region.

A. Wide-Range Tuned Circuits and Oscillators

One of the earlier reports by Karplus (5) on tuned circuits and oscillators at UHF described two fundamental types of tuned circuits which are applicable to the 500- to 1,200-mc region. The first of these is the familiar butterfly circuit with certain innovations or modifications which appear to be advantageous. There will be cited, for example, a circuit designated as a semibutterfly. The circuit is illustrated in Figure 7.1.

The highest impedance in the circuit appears between the points 1 and 2 shown in the figure. In this unit a solid rotor forms an eddy-current shield in the magnetic field and a series-gap capacitor with the stator plates. In this design a wide tuning range is obtained by rotation of a member that does not require any electrical connections. The rotor shaft can be made of insulating material, and a flow of radio-frequency currents through the bearings of this shaft is thus avoided. The rotor can be constructed as a solid block, a configuration which simplifies the mechanical details of assembly.

Although the author states that this circuit is easily applicable for frequencies as high as 1,200 mc, no data are given as to oscillator performance.

The circuit shown will probably suffer severe Q degradation at high frequencies caused by radiation, but complete shielding may partially obviate this difficulty. If the effective Q can be maintained at 300 or 400, then a reasonable order of frequency stability may be effected in an associated oscillator. Consideration is being given to the construction of a model for test purposes using Invar as basic material in order to reduce the temperature sensitivity of the unit.

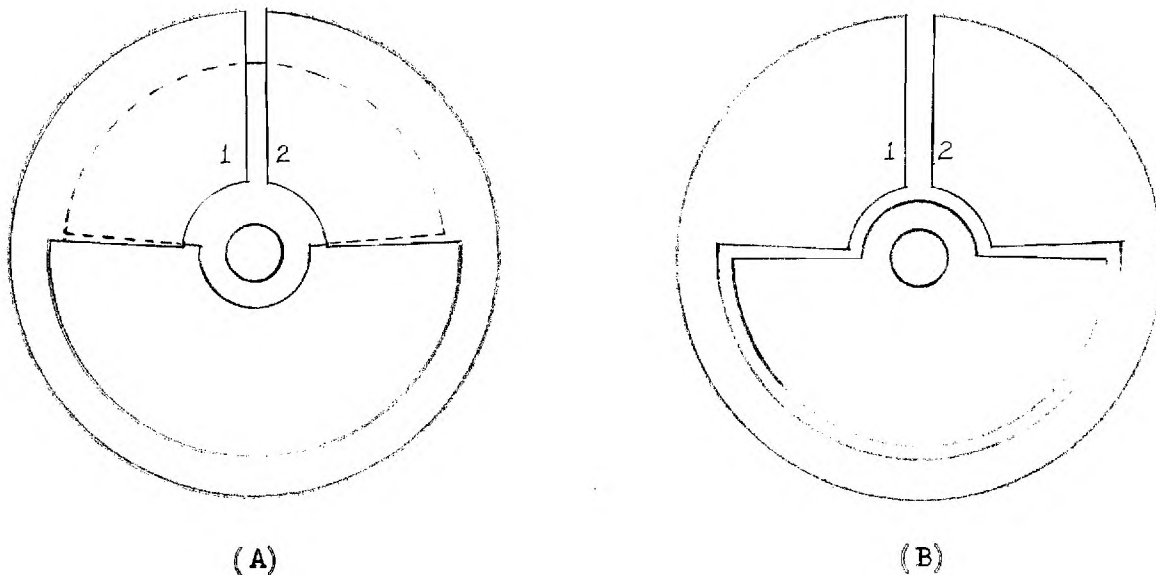


Figure 7.1. Stator and Rotor of Semibutterfly. (Frequency is minimum in A and maximum in B.)

Another basic type of circuit described by the same author is illustrated in Figure 7.2. It consists of two split cylinders mounted on a common axis and with an arrangement which permits a 180° rotation of the inner cylinder. Minimum effective frequency occurs when the two slots are adjacent since in this position the inductances of the two rings are essentially in parallel while the total capacity is not significantly different from that of a single slot alone.

When the inside ring is rotated 180°, as illustrated in Figure 7.2 C, the effective capacitance of the resonant circuit is greatly increased by the presence of the one ring across the gap of the other one while the effective inductance is also maximized.

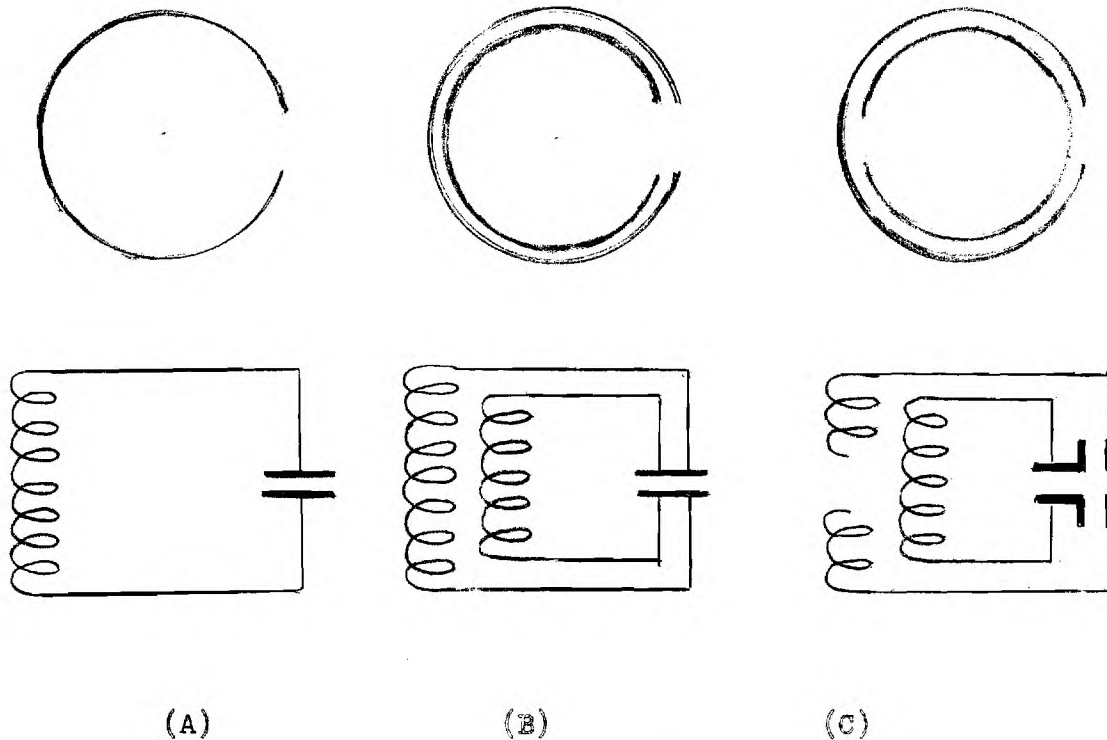


Figure 7.2. Representation of Split-Cylinder Resonator.

At 1,000 mc a Q of not less than 1,000 is claimed if the unit is suitably shielded. Local tests of test models have been conducted on this project to determine the characteristics of the circuit and associated oscillator. A configuration was used which consisted of an outer cylinder two inches long with a 1-1/2-inch outer diameter and a 1/16-inch wall thickness. Inner cylinders were variously configured, some being equivalent in shape to the outer one, some being partially cut away to reduce the percentage change in capacitance and inductance per degree of rotation.

With these configurations oscillations were easily obtained in the 500- to 1,000-mc region utilizing the split-cylinder resonator as a two-terminal impedance shunted between plate and grid of a 6AF4 tube. A silver-plated shield

enclosed the entire oscillator assembly to reduce Q degradation caused by radiations. Although reasonable values of Q may be expected under these conditions, the frequency stability of the oscillator was not satisfactory, being no better than six parts per million per volt change of anode potential (ppm/volt). In addition, the oscillator showed a marked tendency to exhibit a discontinuous jump in frequency between the low and high ends of the band leaving a very large "hole" in the center portion. The results of this brief experiment have led to the conclusion that this configuration is basically unsatisfactory for stable frequency control, although it may find some use as a signal generator of limited tuning range and limited stability.

Isely (6) has described two types of circuits having distributed constants which are of considerable interest at UHF. The first of these utilizes a variable capacitor as a two-wire line as illustrated in Figure 7.3.

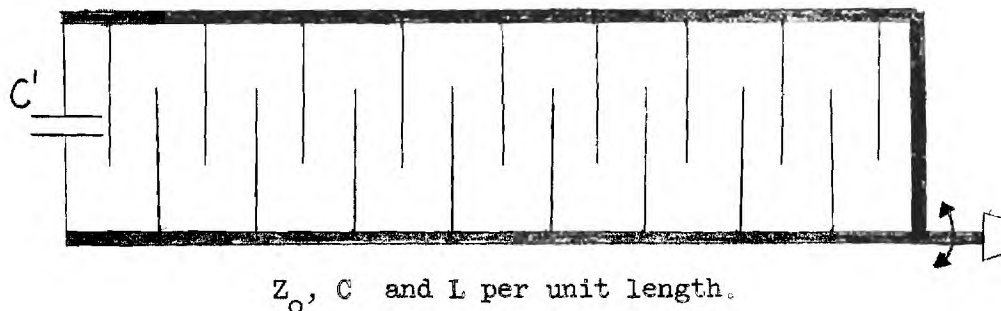


Figure 7.3. A Variable Capacitor as a Two-Wire Line.

A commercial variable capacitor of the type normally used in broadcast receivers was recently tested at this project using the 6AF4 tube shunted across it, as illustrated in Figure 7.3. With rotation of the rotor plates the discretely distributed capacity per unit length varies considerably. The oscillator, utilizing this capacitor, was found to have a tuning range of approximately 520 to 620 mc. Complete shielding of the assembly was found to be

necessary both to prevent excessive sensitivity to external factors and to prevent Q degradation due to radiation. Stabilities slightly better than those found with the split-cylinder were measured. In addition, the oscillator was easy to tune and simple to construct. It suffers, however, from the fact that moving contacts are involved. It is concluded that this configuration, in its present form, is quite useful as a laboratory signal generator of moderate stability. It further appears that if moving contacts can be eliminated and if the capacitor is constructed of a material of low temperature sensitivity that reasonable frequency control may be effected in a range not exceeding 1,500 mc. Some tests in the 1,000-1,500-mc range may be conducted at a later date utilizing Invar as a basis for construction of the capacitor section.

The other type mentioned by Isely concerns a distributed-inductance line. This is constructed by using a solid outer conductor, but utilizing a rotating off-center inner conductor. This inner conductor is solid in part but slotted in the remainder, so that during rotation an inductance variation is obtained by the variation of the mutual inductance when the solid portion approaches or recedes from an adjacent fixed member. A cross section of line is shown in Figure 7.4.

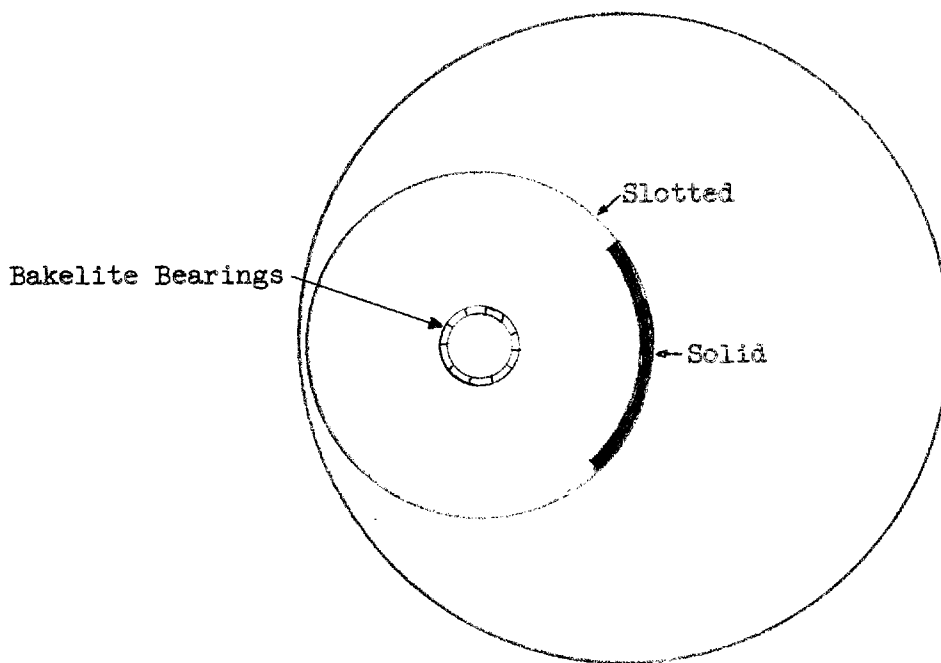


Figure 7.4. Cross Section of Distributed-Inductance Line.

The configuration shown has moving contacts but these can be eliminated by utilizing a bakelite (or equivalent) bearing, thus placing a capacitor across the otherwise shorted end of the line. This configuration shows some promise at frequencies up to 1,500 mc. If time permits, a limited test of such a unit will be conducted.

Another paper (7) discusses a device which is not essentially different in principle from those previously mentioned but which is shown in Figure 7.5 to have considerable variation in mechanical detail. The resonant circuit, designated as a modified butterfly, uses a solid stator as a magnetic shield but provides a slot, or a cut-away section, for tuning purposes. Two separate versions of the circuit are shown in Figure 7.5. In the form shown at the left, the rotor is a solid semicylinder. The stator consists of a cylindrical metallic ring with a slot near the top plus two end plates. The rotor has a small clearance between the ends and the end plates attached to the stator.

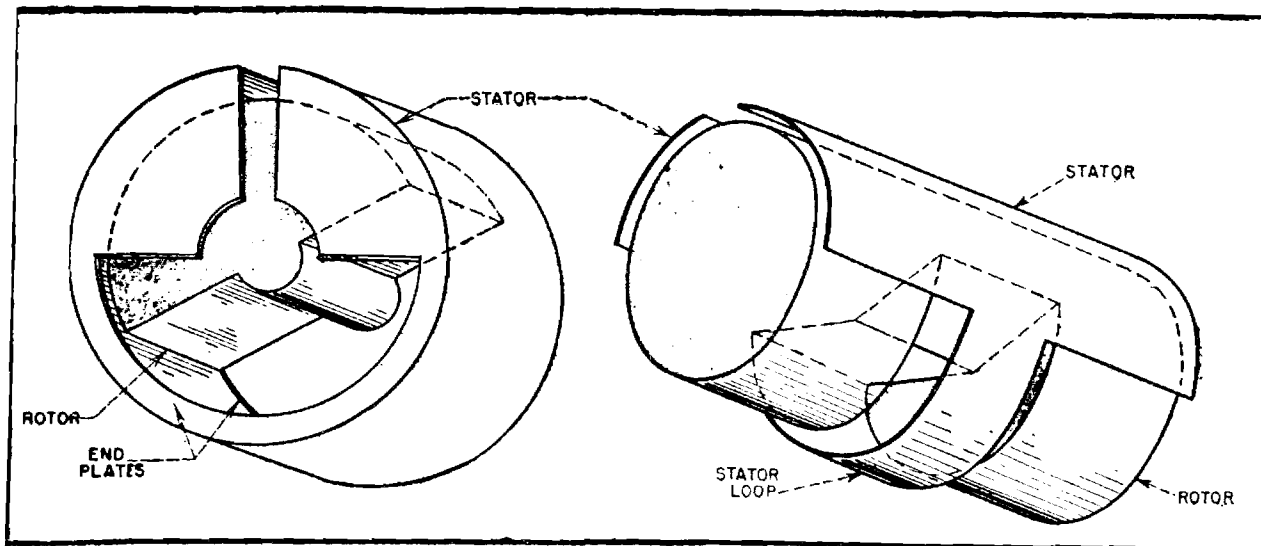


Figure 7.5. Two Versions of the Modified Butterfly.

In the form shown at the right, the end plates are omitted but the stator consists of a slotted semicylinder plus a narrow loop joining the two major portions. The rotor is also modified to become a solid cylinder with a single transverse slot. The inductance variations now depend upon changes in inductance of the loop brought about by the shielding action of the rotor while the capacity variations are much the same as for the type with end plates.

The modified butterfly is claimed to provide linear tuning over an approximate two-to-one range between 500 and 900 mc. Consideration may be given to the possibility of extending its upper frequency range above 1,000 mc and of utilizing low-expansion materials in construction.

B. Automatic Frequency Control at UHF

The application of reflex-klystron oscillators as signal sources has focused attention on automatic frequency control (AFC) as a means of obtaining excellent frequency stability at UHF and SHF. The reflex klystron lends itself admirably to the AFC process because a small change in reflector voltage produces a large change in oscillator frequency.

The basic method of providing the necessary circuit arrangements follows a system devised by R. V. Pound (8). Although his method is well-known, it is considered desirable to include a brief summary here to complete a partial resume of frequency-control methods.

The basic system, as described by Harrison (9), is shown in Figure 7.6. A hybrid junction furnishes a sample of the output of the klystron. When the oscillator frequency coincides with the resonant frequency of the cavity, there is no r-f signal at mixer crystal No. 1 and no i-f signal at mixer No. 2. A shift in frequency produces an r-f signal at the first crystal mixer which becomes modulated at the intermediate frequency and reflected to the second mixer where it is demodulated to produce an i-f signal. The phase and amplitude of the demodulated i-f signal are determined by the relation between the klystron frequency and the cavity frequency. The phase mixer compares the demodulated i f with the original source and produces a signal which corrects the klystron frequency.

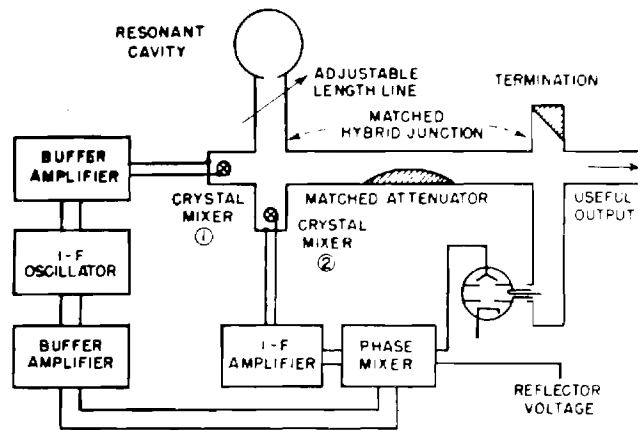


Figure 7.6. The Pound Stabilization System.

The possibilities of utilizing temperature-compensated coaxial cavities with this arrangement are self-evident and will be given careful consideration in the frequency regions above 1,000 mc.

VIII. CONCLUSIONS

The principle of temperature compensation, previously successfully applied at 300 mc to a brass-Pyrex resonator, appears to be also satisfactory at higher frequencies. The utilization of silver-plated Pyrex as a center conductor now appears to be unsatisfactory because of a tendency of the glass to lose its silvered surface at points of pressure contact. The use of other materials such as fused quartz or metals of low expansivity is indicated.

Cavity control of oscillators can be achieved in several ways but a desirable configuration is one in which the oscillator is located within the cavity at the open end of the center conductor and is connected to the outer conductor by a small variable-series capacitor. Preliminary tests indicate that three independent parameters, namely, series capacitive reactance, cavity length and cavity characteristic impedance, may be selected to provide optimum operating conditions.

Control of oscillators by the use of the high-overtone responses of quartz crystals now appears feasible provided that sufficient sensitivity of elements within the feedback loop can be achieved. The problem of sensitivity applies both to the magnitude of discriminator output voltage in the immediate vicinity of crystal resonance and to the magnitude of frequency deviations effected by the reactance tube.

Control of oscillators at UHF has been effected by other agencies and by somewhat diverse and often novel means. The various assemblies include modified butterfly-tuning units, distributed capacity lines and split-cylinder and variable-inductance resonators. At microwave frequencies the Pound stabilization system has been widely used. Variations of some of these units utilizing low expansivity materials appear to have possible application for the objectives of this project. The compensated cavities described in this report may find application in the stabilization system.


IX. PROGRAM FOR THE NEXT QUARTER

The investigation of cavities will be continued. The tunable 600-mc cavities, previously scheduled for assembly and test during the present quarter, will be completed and tested upon the receipt of other materials. Invar or fused quartz will be used to replace the Pyrex which has shown unsatisfactory retentivity of silvered surface. Communications with a manufacturer of fused quartz will be continued to plan the fabrication of a complete coaxial resonator from quartz. The use of Invar will be considered in detail for coaxial resonators and for other types of tuning units.

In the field of oscillators continued attention will be devoted to the series-tuned cavity-controlled oscillator described in this report. It is planned to extend the frequency range upward in conjunction with studies of means for obtaining optimum operating conditions. Other methods of frequency control using variations of novel devices will be given a limited investigation to determine any feasibility of utilization at frequencies above 1,000 mc.

Some further attention will be directed toward automatic frequency control with quartz crystals, with emphasis upon methods of increasing the sensitivity of the control devices. At the same time, consideration will be given to the possibility of using a synchronizing process to exploit the observed high-frequency response of the quartz crystals.

Respectfully submitted:


Donald W. Fraser
Project Director

Approved:


J. E. Boyd, Head
Physics Division


Herschel H. Cudd, Director
Engineering Experiment Station

X. IDENTIFICATION OF KEY TECHNICIANS

This project is under the direction of Mr. Donald W. Fraser who devotes one-third time to this work at present. He is Assistant Professor of Electrical Engineering at Georgia Tech and holds the degree of Master of Science in Electrical Engineering from this institution. He worked on station project 131-45, "High Frequency Crystal Controlled Oscillators," devoting approximately one-fourth time to it. His other experience includes five years of electronic testing and research in the U. S. Navy.

Mr. James C. Sellers joined the project as Electronics Technician at its onset. He is currently devoting full time to the project. Mr. Sellers previously was engaged for eight years in nuclear instrumentation with the AEC at Oak Ridge, Tennessee, where he had extensive experience as a technician in the design, assembly and testing of electronic circuits.

Mr. James C. Hogg, Jr., Assistant Research Professor, devotes approximately one-third time to the project. Mr. Hogg holds the degree of Master of Science in Electrical Engineering from the Georgia Institute of Technology. Mr. Hogg has had extensive experience in circuit design and oscillators, both in the industrial and the research field. He was employed on a full-time basis on the S.C.E.L. projects, "High Frequency Crystal Controlled Oscillator Circuits" and "Investigation of Frequency Control Above 150 Mc."

Mr. Edward G. Holmes has recently joined the project. Mr. Holmes holds the degree of Master of Science in Electrical Engineering. His experience in the electronics field includes three years of work with frequency-measuring apparatus and broadcasting equipment, two years as Electronics Officer in the U. S. Navy and three years of research and development work in UHF and microwave equipment. He is now devoting approximately one-half time to the project and plans to increase this to full time in the next several months.

Short-term need for additional personnel was filled during December and January by the services of Mr. John Jamgochian, Jr. Mr. Jamgochian holds the degree of Master of Science in Electrical Engineering from the Georgia Institute of Technology. He has had several years of experience as supervisor of installation and maintenance of airborne electronic equipment in naval aircraft squadrons. At Georgia Tech he previously has had some part-time work on another electronic project.

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ENGINEERING EXPERIMENT STATION
of the Georgia Institute of Technology
Atlanta, Georgia

PROGRESS REPORT NO. 5

PROJECT NO. 229-198

PRECISION FREQUENCY CONTROL TECHNIQUES
(500 mc and Higher)

By

DONALD W. FRASER

-O-O-O-O-O-

CONTRACT NO. DA-36-039-sc-42590

DEPARTMENT OF THE ARMY PROJECT: 3-99-11-022
SIGNAL CORPS PROJECT: 33-142B

-O-O-O-O-O-

FEBRUARY 1, 1954, TO MAY 1, 1954

PLACED BY THE U. S. ARMY
SIGNAL CORPS ENGINEERING LABORATORIES
FORT MONMOUTH, NEW JERSEY

ENGINEERING EXPERIMENT STATION
of the Georgia Institute of Technology
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I. PURPOSE

The purpose of this project is threefold: (a) to continue work on stabilization of oscillators between 500 and 3000 mc, using cavity resonators, (b) to continue work on frequency control utilizing high-order overtones of quartz-crystal blanks and (c) to undertake any other investigations which may arise during the course of the work outlined in (a) and (b) above, or which may be mutually agreed upon between the Contractor and the Contracting Officer or his representative.

By agreement with the sponsor, investigations of resonances below 500 mc may be prosecuted as preliminary steps in determining the feasibility of frequency control by the phenomena under study. In addition, cavity resonators previously under construction and designed to provide control of frequencies below 500 mc may be completed and tested as aids in perfecting measurement techniques which will later be applied to the range of frequencies above 500 mc.

II. ABSTRACT

Two primary objectives have been emphasized during the period of this report. The first has been the continued development of coaxial-cavity resonators of minimum temperature sensitivity, the second has been an effort to determine optimum methods of construction of cavity-controlled oscillators in the 500- to 1000-megacycle region.

Three models of cavities have been developed. The first, using a brass outer conductor and a silver-plated Pyrex inner conductor, is temperature-compensated. It is provided with an arrangement which permits resonator tuning without affecting the hermetic sealing which is required to eliminate the effects of humidity on frequency stability. A second cavity, utilizing a Vycor center conductor, is uncompensated and nontunable. The third utilizes a center conductor which is constructed of Invar and which is rigidly secured to a brass end-plate. Of the three cavities, the first two have demonstrated results which are considered to be satisfactory. The one containing the Invar center conductor has been quite inconsistent in temperature-frequency response. This may be caused by a transfer of stresses within the outer conductor to the center conductor via the rigid mounting.

Continued attention has been devoted to cavity-controlled oscillators using a small series capacitor. Experiments to determine the effect of characteristic impedance and of physical size of the cavity have been conducted. An oscillator which has demonstrated frequency stabilities of better than one-half part per million and is tunable over a 20 per cent frequency range near 500 mc has been constructed. Several other oscillators have been constructed; they are all consistent in action but somewhat less stable than the aforementioned.

A small amount of continued work has been applied to the problem of automatic frequency control. Discriminator action using a high-frequency cavity as a frequency-sensitive device has been demonstrated. No application of the output to control of frequency has been attempted during the period of this report.

III. CONFERENCES

Messrs. James C. Hogg and Edward G. Holmes, who are technical personnel involved in this project at Georgia Institute of Technology, met with representatives of the Signal Corps in conference at the Squier Laboratories, Fort Monmouth, New Jersey, on April 15, 1954. The purpose of this meeting was to discuss the various factors related to this project, to further mutual understanding of the problems involved on proposed investigations and to adapt the program of research to those topics considered to be of paramount interest to the Signal Corps.

With the objective of furthering the state of the art of frequency control in the 500- to 3000-mc region, the following topics were considered at length. Relative to past work the following were discussed: (a) the temperature compensation of a nontunable brass cavity, (b) low-expansivity cavities utilizing Stupalith as a center conductor, (c) loop-coupled, two-terminal, cavity-controlled oscillator, (d) shock-excited crystal output and (e) discriminator output using a crystal as the frequency-sensitive device. Discussion of the present work included (a) tunable compensated cavities, (b) series-capacitor, cavity-controlled oscillator, (c) discriminator output using a cavity as the frequency-sensitive device and (d) klystron at 600 mc as tool for AFC testing. Future planning included (a) series-capacitor (or other network), cavity-controlled oscillator extended in range to 1500 mc, (b) Invar cavities (low expansivity), (c) synchronization of an oscillator using output of shock-excited crystal, (d) AFC simplified Pound System and (e) discriminator output using dual cavity.

The following conclusions were reached by the representatives of the Signal Corps at Squier Laboratories and those of Georgia Institute of Technology: As regards past work, it was decided that experiments with compensated cavities would be discontinued temporarily and that investigations of low-expansivity nickel-steel cavities should be conducted. Work should continue on the series-capacitor, cavity-controlled oscillator to find the optimum parameters for best frequency stability and to obtain the characteristics at higher frequencies. Work is to be planned to develop an automatic-frequency-control system for the VHF region which will be a simplified version of the

Pound System, at sacrificed accuracy. A UHF discriminator using a dual-cavity arrangement is part of this experiment, as well as overtone crystals in a modified UHF discriminator. In the more distant future an attempt is to be made to synchronize a UHF oscillator with a gated crystal-oscillator..

IV. COAXIAL-CAVITY RESONATORS

All of the previous progress reports submitted through this project have described various steps in the design and development of coaxial cavities. A primary objective of design has been the attempt to incorporate into the resonator properties of small temperature sensitivity. Compounds and elements having low coefficients of expansivity have been tested as possible materials in construction of the desired resonators. It has been evident that a reasonably small order of temperature insensitivity may be achieved by utilization of such materials, if problems of fabrication are not so difficult as to invalidate the advantages otherwise gained.

The greatest theoretical insensitivity may be obtained by some method of compensation. The previous reports have described compensated nontunable cavities designed for frequencies up to 600 mc and usable in principle to higher frequencies. The present report describes a resonator which is similarly compensated and which in addition, is tunable over a moderate frequency range, from 540 mc to 600 mc, approximately. The temperature characteristics for one portion of the available band are illustrated by curves of Figure 4.4.

The temperature characteristics of two nontunable cavities are likewise illustrated. One cavity utilizes a center conductor composed of Vycor, the other one of silver-plated Invar. Compensation principles are not applied to the first of these but are applied to the second.

A. A Tunable Temperature-Compensated Coaxial Cavity

The principles of design and construction of a tunable compensated coaxial cavity were discussed in Progress Report No. 3.(1) A cross-sectional view of the then-contemplated cavity was shown there. The finished resonator is substantially the same, but a few mechanical variations have been added to assure structural stability. A cross section of the tunable resonator is shown in Figure 4.1 and details of construction are given in Figures 4.2 and 4.3.

A limited number of heat-cycling runs have been made to determine the temperature characteristics of the cavity. These are illustrated in Figure 4.4. The curve at the top of the figure illustrates a temperature cycle

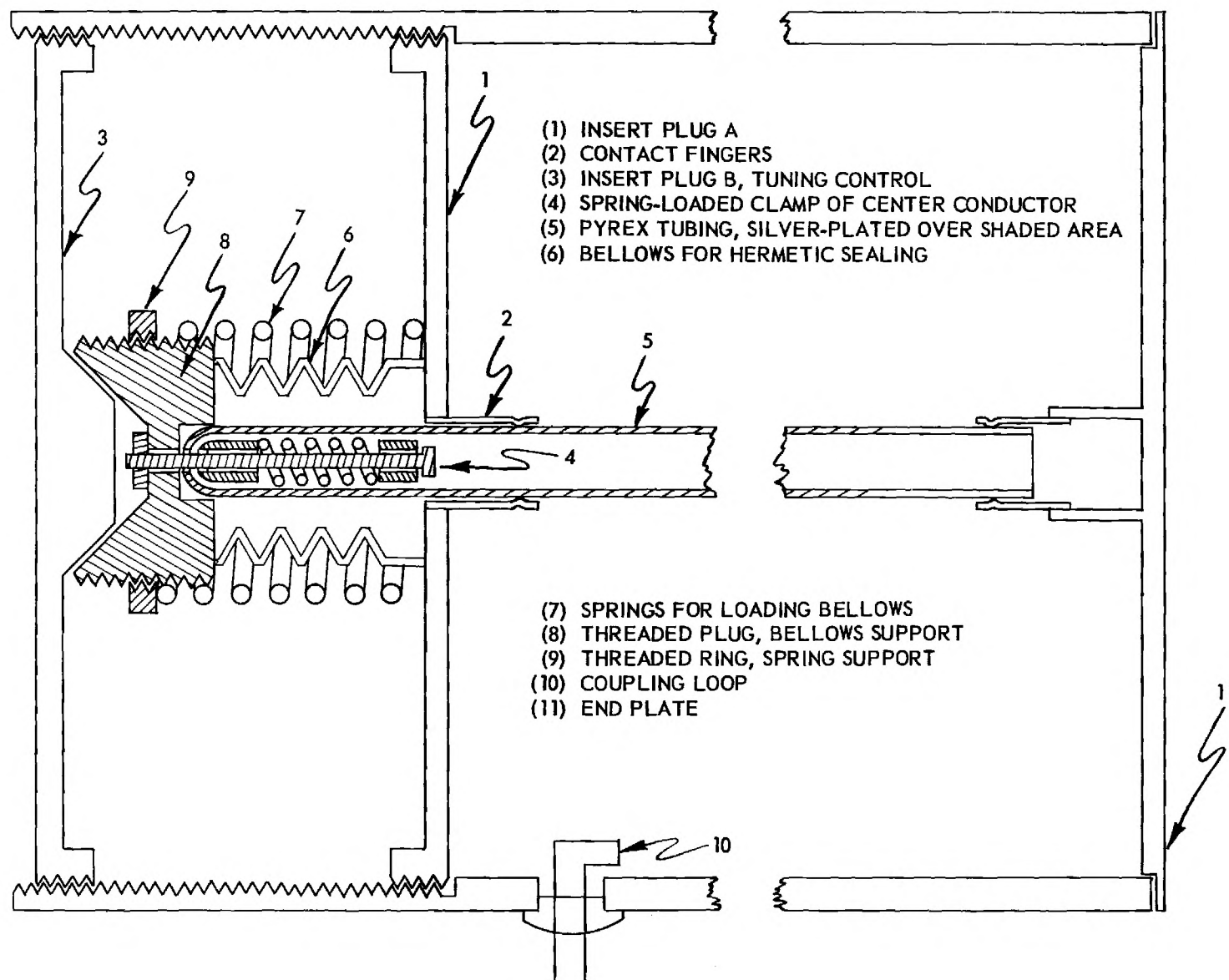
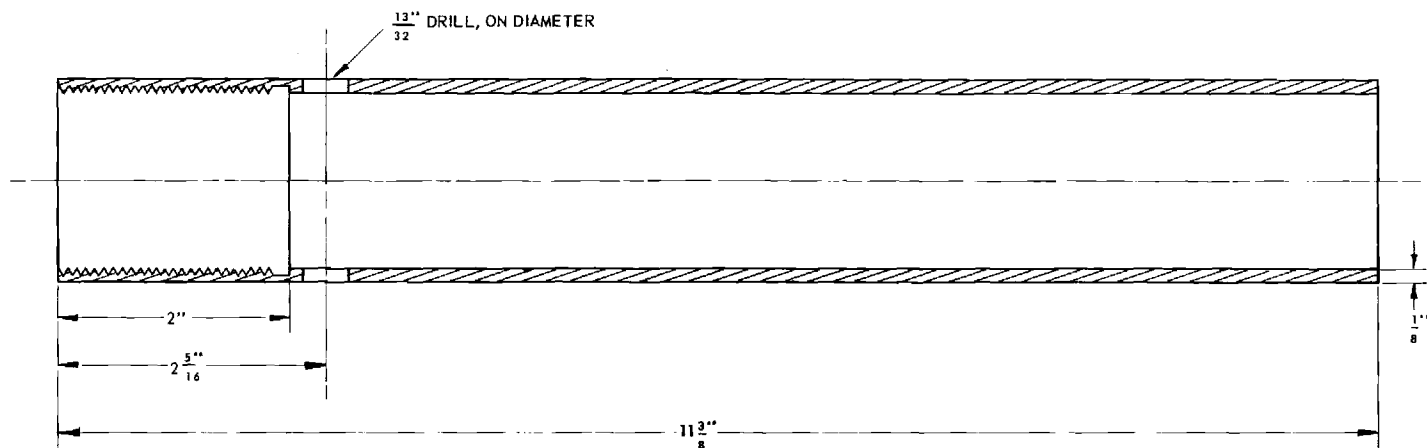
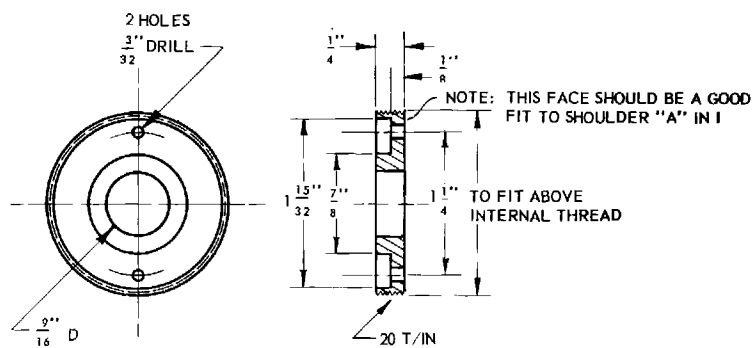


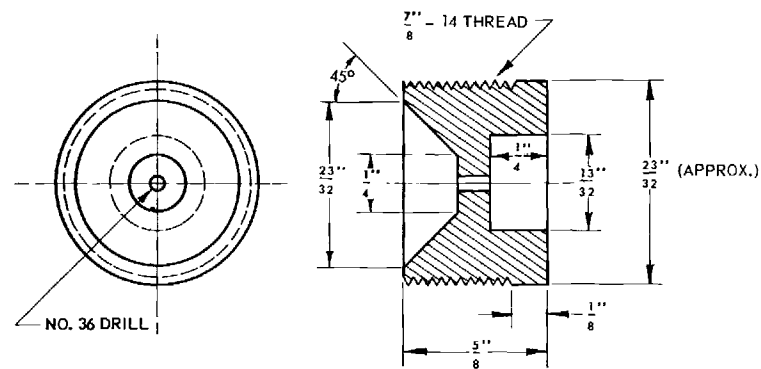
Figure 4.1. Tunable Compensated Cavity.



1. (Hard Drawn Yellow Brass Tubing, $1\frac{1}{4}$ " O. D. $\frac{1}{4}$ " Wall)

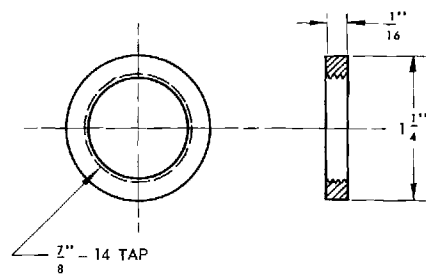


Part No. 1 of Figure 4.1 (Yellow Brass)

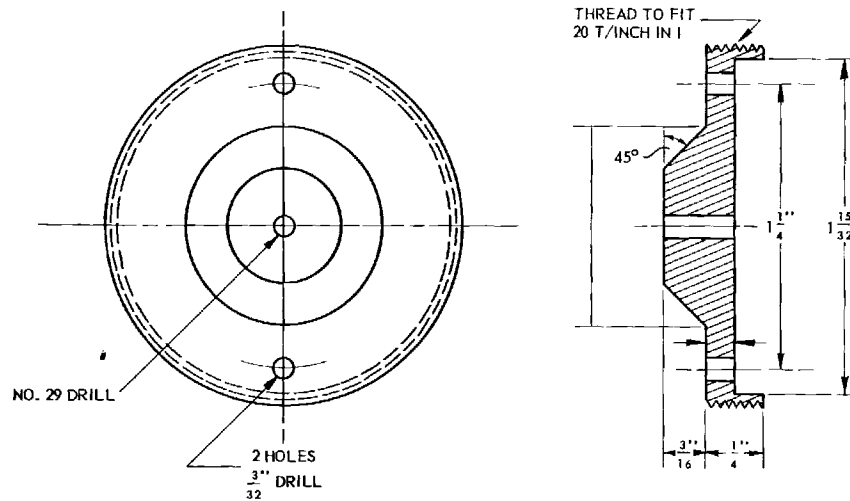


Part No. 8 of Figure 4.1 (Yellow Brass)

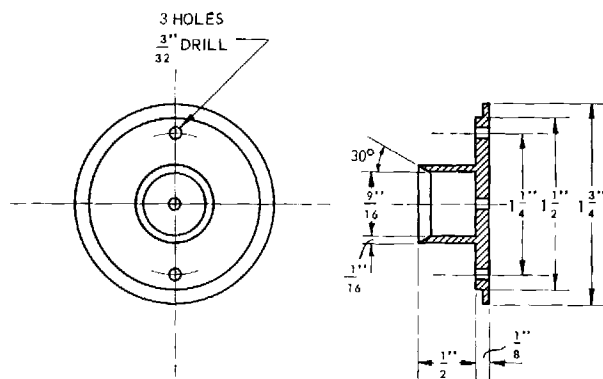
Figure 4.2. Details of Construction, Tunable Compensated Cavity (Part I).



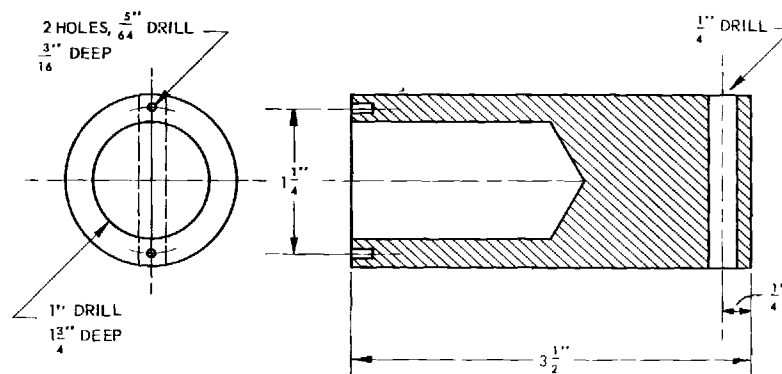
Part No. 9 of Figure 4.1 (Yellow Brass)



Part No. 3 of Figure 4.1 (Yellow Brass)



Part No. 11 of Figure 4.1 (Yellow Brass)



Wrench (Cold Rolled Steel)

Figure 4.3. Details of Construction, Tunable Compensated Cavity (Part II).

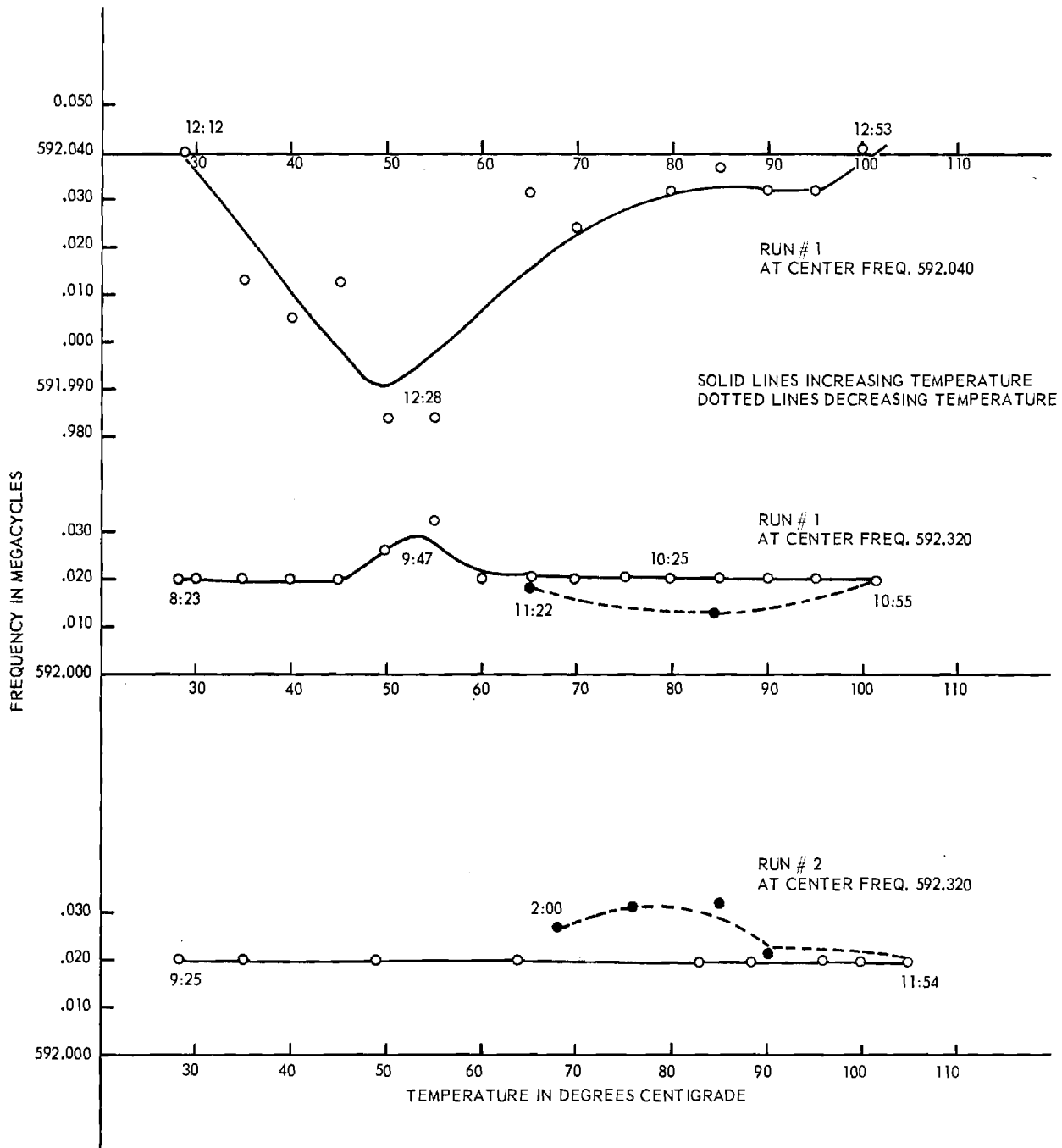


Figure 4.4. Temperature Characteristics of Tunable Compensated Brass Cavity.

produced by heated air flowing over the cavity and raising the temperature in the space around cavity from 29° C to 100° C in the elapsed time between 12:12 and 12:53. These times and other representative ones are shown on the figure.

It will be noted that a sharp frequency-response lag occurs in the vicinity of the fifty-degree point of the curve. This could be caused by a thermal delay within the heavy-walled brass cavity, a phenomenon that has been noted before when cavities have been subjected to rapid heating. No comparable action was observed in the other two runs illustrated. In these a much slower rate of heating was adopted.

In the upper curve a maximum frequency deviation of about 55 kilocycles was observed. In the lower two curves, for which the cavity was tuned to a slightly different frequency, the frequency deviation was in most cases so small as to be hardly measurable. As indicated temperature sensitivity of approximately zero is observed.

A note as to the accuracy of these curves must be added. The measuring technique, as described in detail in Progress Report No. 1 (2), utilizes two markers superimposed upon the response curve of the cavity. Accuracy of the measurements depends upon the ability of an operator to reset these spots to an identical previous position during any one measurement. Tests to determine the resetting error have been conducted. It has been demonstrated that an experienced operator can reset with an error of not more than one part in 10^5 . At 600 mc, the approximate frequency of the cavity, a maximum error of 6 kilocycles can be produced by resetting variations. To this error must be added the possible error of the frequency-measuring equipment. The frequency meter presently used on this project, a Gertsch model FM-3, has a claimed maximum error of one part in 10^5 . This also gives, at 600 mc, a maximum error of 6 kc and if this is added to the maximum resetting error a total possible deviation of plus or minus 12 kc is seen to exist. It is reasonable to assume that the actual error is not in excess of half the possible maximum, so that the lower curves of Figure 4.4 might be presumed to have a possible total deviation, within the 77-degree change, of 12 kc. This represents a temperature sensitivity of about 0.25 part per million per degree centigrade.

B. Uncompensated Cavity with Vycor in Center Conductor

It is evident that the complexity of construction existing in the compensated cavity is unwarranted provided equivalent characteristics can be achieved by simpler means. The attractive low-expansion characteristics of certain materials indicate that it should be possible to utilize these in the desired temperature-insensitive resonator. However, problems of fabrication may overbalance the advantages otherwise gained. For example, the ceramic Stupalith which was previously reported upon failed to retain a silvered surface upon exposure to soldering temperatures and, as a result, appears unsatisfactory for use. Fused quartz, as another example, is known to be difficult to fabricate. The use of low-expansion materials for the center conductor alone appears to be possibly more satisfactory because the outer conductor and end pieces can be constructed of brass or other easily machined materials. The problem then remaining is that of mounting the center conductor in such a manner that the unequal expansions of the inner and outer conductors will not produce off-centering stress upon the forms.

Earlier tests with uncompensated cavities failed to realize a temperature insensitivity equal to that determined by the coefficient of expansivity of the center conductor. It was theorized that stresses and strains introduced into the center conductor may have produced added errors to account for the discrepancies in temperature sensitivity. In an attempt to establish a method of mounting wherein no rigid contact exists between the inner and outer conductors, the configuration illustrated in Figure 4.5 was adopted. In this arrangement, the free end of the center conductor is held firmly, but not rigidly, by spring fingers. The other end, which is electrically active, is soldered to another set of spring-finger contacts.

The electrically active portion of the conductor is located between the soldered tips (A) and the end of the cross-hatched section at the left. The plug (B) is threaded and may be forced tightly against the shoulders as illustrated in order to effect a satisfactory electrical bond. The plug (C) is used to seal the cavity in order that it may be filled with an inert gas under reduced pressure.

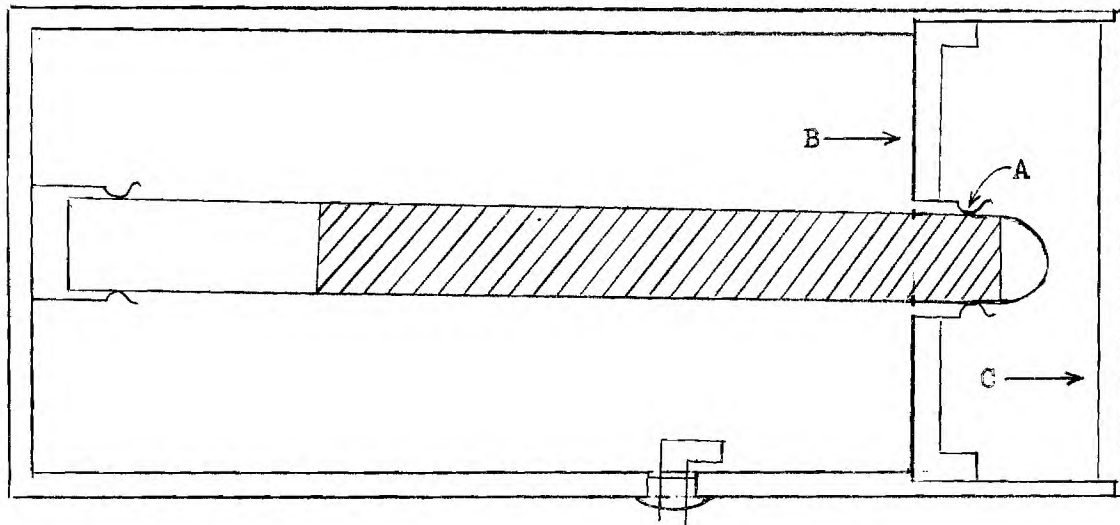


Figure 4.5. Arrangement of Parts of Uncompensated Cavity with Vycor Center Conductor.

The results of several frequency-versus-temperature runs are illustrated in Figure 4.6. Although the upper curve is labeled Run No. 1, there were actually several temperature-cycling unrecorded runs completed prior to recording the data for these curves. It was observed during these cycles that considerable erratic frequency variations occurred during the cycling process, but that the deviations became less pronounced with subsequent cycles. It appears that some further erratic behavior may account for the abrupt dip between 30 and 50 degrees in Curve No. 1. No other known information is available to explain this anomaly.

If Runs 2 and 3 only are taken into account, it is found that the maximum frequency variation was approximately 40 kc. The average deviation in Run 2 represents less than one-half part per million per degree centigrade while that of Run 3 is slightly greater. These results indicate that a cavity of this type is satisfactory for applications where moderate orders of stability are satisfactory. However, it appears that compensated cavities must be utilized if higher orders of stability are required.

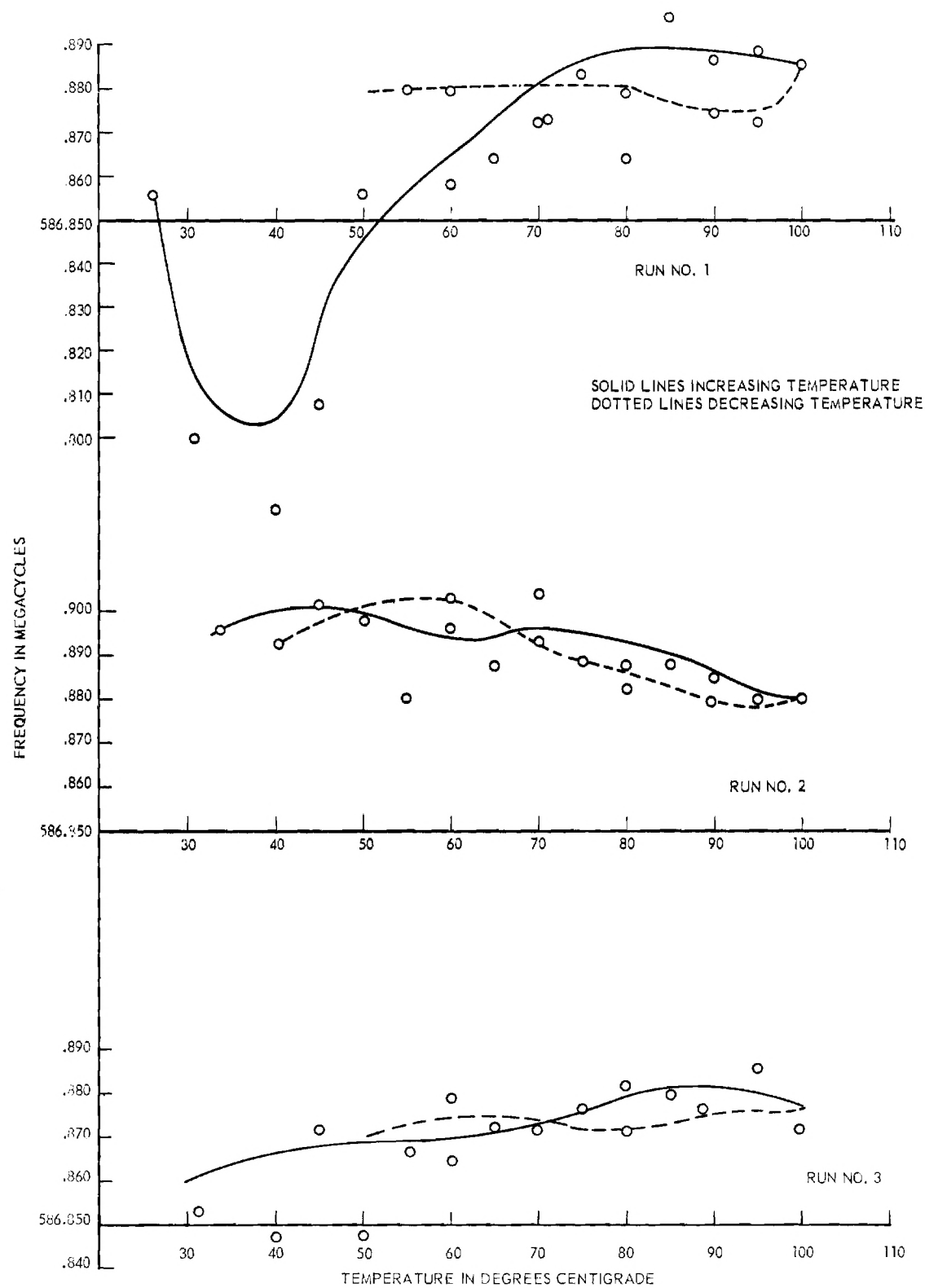


Figure 4.6. Temperature Characteristics of Uncompensated Cavity with Vycor Center Conductor.

C. Compensated Nontunable Cavity with Invar Center Conductor

The recent acquisition of Invar rod has permitted initiation of tests of cavities using this material in the center conductor. The same configuration as that previously used for compensation of Pyrex center conductors has been applied. This is illustrated in Figure 4.7. It will be noted that the Invar rod is secured firmly to the end-plate by a machine screw inserted in the end of the rod. This method differs from that employed with Pyrex. In the latter arrangement, the Pyrex tubing was held with moderate firmness by a spring-loaded screw and derived its principal rigidity from the support of spring fingers at each end of the cavity proper.

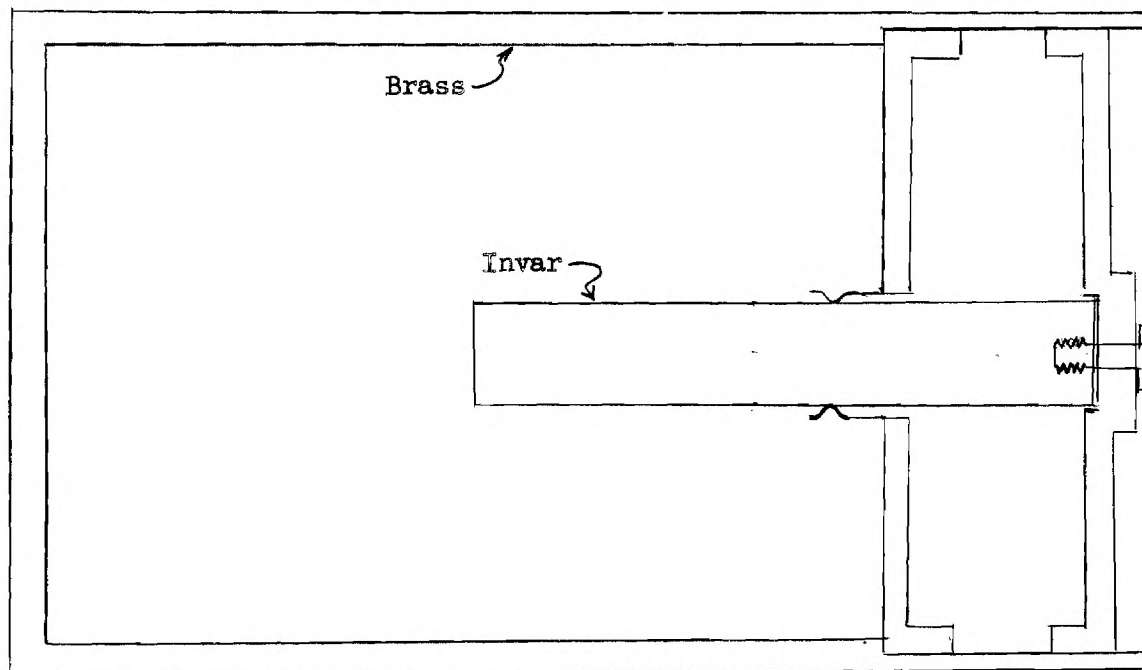


Figure 4.7. Compensated Cavity with Invar Center Conductor

The compensating section (which is exaggerated in length in this sketch) is represented by the spacing between the two plugs at the right. In this case, this spacing should be approximately $1/20$ of the length of the electrically active part of the center conductor since Invar has a coefficient of expansivity of approximately unity and brass a corresponding coefficient of about twenty.

A number of temperature runs have been made with this cavity. The results have been inconsistent, but in no case has the theoretical temperature insensitivity of the combination been attained. These effects may have been due to flexural stresses transferred to the inner conductor via the rigid mounting previously mentioned. These stresses may be expected to be unpredictable both in magnitude and in direction. An improvement in temperature characteristics might be effected by adoption of a spring-loaded type of mounting to avoid these stresses and strains. Another alternative is to fabricate a cavity from a solid bar of Invar, thus avoiding threaded joints or soldered connections. This latter method is now being studied and, if adopted, will be the subject of a later report.

V. CAVITY-CONTROLLED OSCILLATORS

Two distinct types of cavity-controlled oscillators have been under investigation by this activity. In one, the vacuum tube is exterior to the cavity and maintains its coupling to the cavity by means of a wire loop which is inserted into the magnetic field. In the other, the tube is interior to the cavity and maintains coupling by conductive means.

It has been previously reported that the loop-coupled oscillator represents a resonator which is simple to construct and which provides excellent orders of stability. There is, unfortunately, a frequency limitation inherent in this system which is occasioned by the unavoidable leakage inductance exhibited in that portion of the connecting leads between the loop proper and the internal elements of the vacuum tube. It has been estimated that frequencies in the order of 500 to 600 mc would constitute the upper limit of precise control by the loop-coupled method. This contention is rather well confirmed by data presented in the next paragraph which describes efforts to produce cavity control in the neighborhood of 570 mc with unsatisfactory results.

The conductively coupled cavity was discussed in some detail in Progress Report No. 3 (1), with emphasis on the version which employs a small series capacitor as a means of improving frequency stabilization. Continuing studies of this configuration have been made during the period of this report. A series of center conductors representing various characteristic impedances have been constructed as vehicles for testing the effect of Z_0 upon oscillator performance. The latter paragraphs of this section give details of the results.

A. Loop-Coupled Cavity Above 500 Mc

The same principles of construction which were earlier employed in a lower frequency (470 mc), loop-coupled, cavity-controlled oscillator were employed using a higher frequency coaxial cavity. In view of the fact that the lower frequency model had demonstrated excellent short-term frequency stability of better than 0.5 part per million per volt change of anode potential (ppm/v), it was probable that comparable results might be obtained with the higher frequency version.

The arrangement utilized is illustrated in Figure 5.1. The tube (oscillator) assembly is secured to a circular plate which may be rotated and secured by screws at any desired position. In this way the coupling loop may be rotated from positions of maximum coupling to those of minimum coupling. The tuning slug, designated in the figure, may likewise be rotated and secured at any desired angle. It can change the resonant frequency of the cavity by approximately 50 mc.

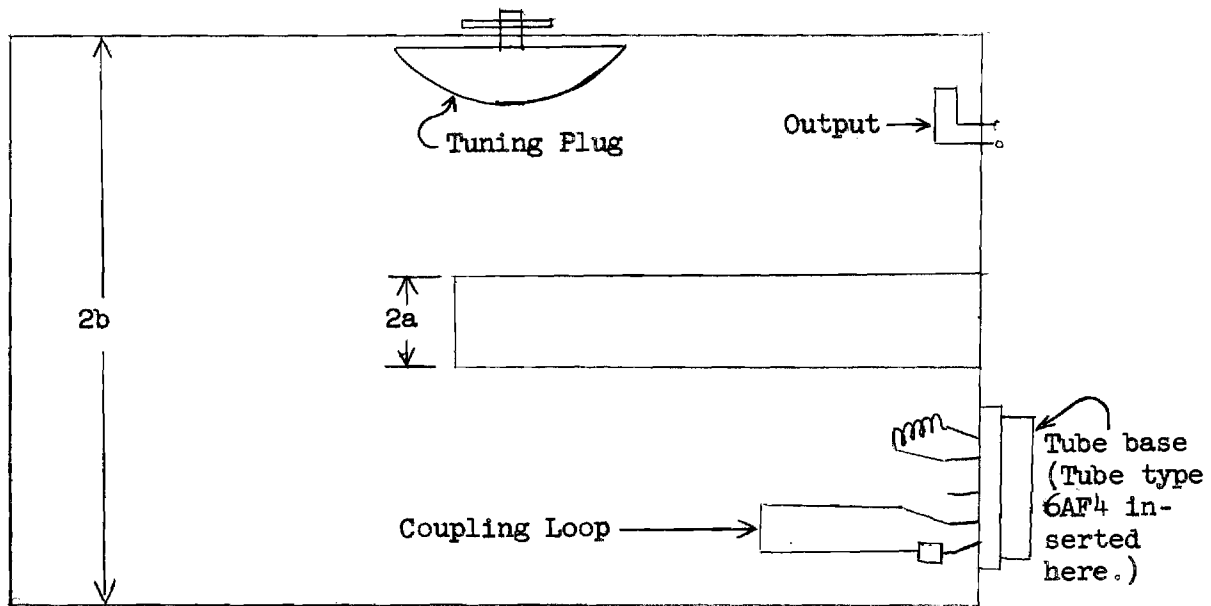


Figure 5.1. Loop-Coupled Oscillator and Cavity

The results of tests on this cavity were unsatisfactory. Although there was a definite improvement in the stability of the oscillator when within the cavity as compared to its condition when free-running outside the cavity, there was little evidence of a true "lock" to the cavity. The frequency stability was usually not better than 3 ppm/v, a very poor comparison to the stability of the 470-mc oscillator.

One possible explanation for the much poorer stability may be found in the cavity dimensions and their effect upon the cavity Q . The quality factor Q of a coaxial cavity is given (4) as:

$$Q = \pi f_a / \alpha v, \quad (5.1)$$

where α is the attenuation in nepers per meter and is given by

$$\alpha = 1/2 \sqrt{\frac{\pi f_a \mu_2 E_1}{\sigma_2 \mu_1} (1/b + 1/a) \frac{1}{\ln b/a}}. \quad (5.2)$$

In this formula, b and a refer to cavity dimensions as shown in Figure 5.1. It is seen from equations 5.1 and 5.2 that Q varies inversely as the term $(1/b + 1/a)$. Hence, as the cavity dimensions are reduced, the ratio b/a being held constant, the Q is reduced proportionately. The data obtained with this cavity, and comparable results with conductively coupled cavities described in the next subsection, indicate that this change of Q -factor due to cavity dimension is of considerable significance in oscillator stability. In the near future, a loop-coupled oscillator similar to the one described above but using a cavity of larger dimensions will be tested in an attempt to confirm the above conclusions.

B. Series-Tuned Cavity-Controlled Oscillators

Progress Report No. 4 (3) described a series-tuned, cavity-controlled oscillator which was undergoing study to determine optimum operating conditions. It was pointed out that the addition of a small capacitive reactance in series with the input impedance of the cavity tended to steepen the curve of total reactance versus frequency. This, in turn, should improve the frequency stability of the oscillator.

Other parameters affect the theoretical frequency stability, of which one of the more important is found to be the cavity's characteristic impedance. The magnitude of inductive reactance furnished by the cavity at any given frequency is directly related to its characteristic impedance. It follows that when the two pertinent reactances of the complete oscillator, i.e., cavity

reactance and the negative of the tube reactance, are plotted upon the same diagram they will intersect at an angle whose magnitude is dependent upon their respective slopes. A measure of oscillator stability is found by assuming a shift in the tube reactance curve, thus producing a new intersection on the cavity reactance curve. The two intersections, projected upon the frequency axes, indicate the frequency shift which may be expected to occur.

These relationships are illustrated in Figure 5.2, which represents the reactance $|Z(j\omega)|$ of two cavities which have different characteristic impedances, Z_1 and Z_2 , but are otherwise similar. The sums of the reactance of each cavity and of small series capacitors are illustrated by the dotted lines. It can be seen that these latter curves are steeper at the points of intersection, A and B, with the tube reactance line than when measured in the absence of the series-capacitive reactance. It is further evident that an optimum theoretical frequency stability should result from a cavity reactance curve which exhibits a vertical slope at the point of intersection with the tube line and that this condition could be approached by lowering the characteristic impedance of the cavity and/or increasing the series capacitive reactance.

Experimental investigations to determine the practical aspects of this theory have been conducted in part during the period of this report and are still in progress. In order to provide convenient vehicles for attaining several different values of characteristic impedance and Q, outer conductors of two different diameters and five inner conductors of widely varying diameters were constructed. Figure 5.3 assists in visualization of the cavities resulting, including the five conductors (with end-plates). The value of characteristic impedance for each is shown directly above its respective center conductor. The relative sizes of inner and outer conductors may be visualized by comparing the center conductor to the end-plate.

The method of mounting the tube was illustrated in the previous report but is repeated here in Figure 5.4 for purposes of clarity. The tube shown herein represents either a type 6AF4 or its subminiature version, the 5718.

The capacitor illustrated in the figure was selected to provide both a relatively small magnitude of capacity and a wide tuning range. Two different models of capacitors have been utilized. One, designated as the High

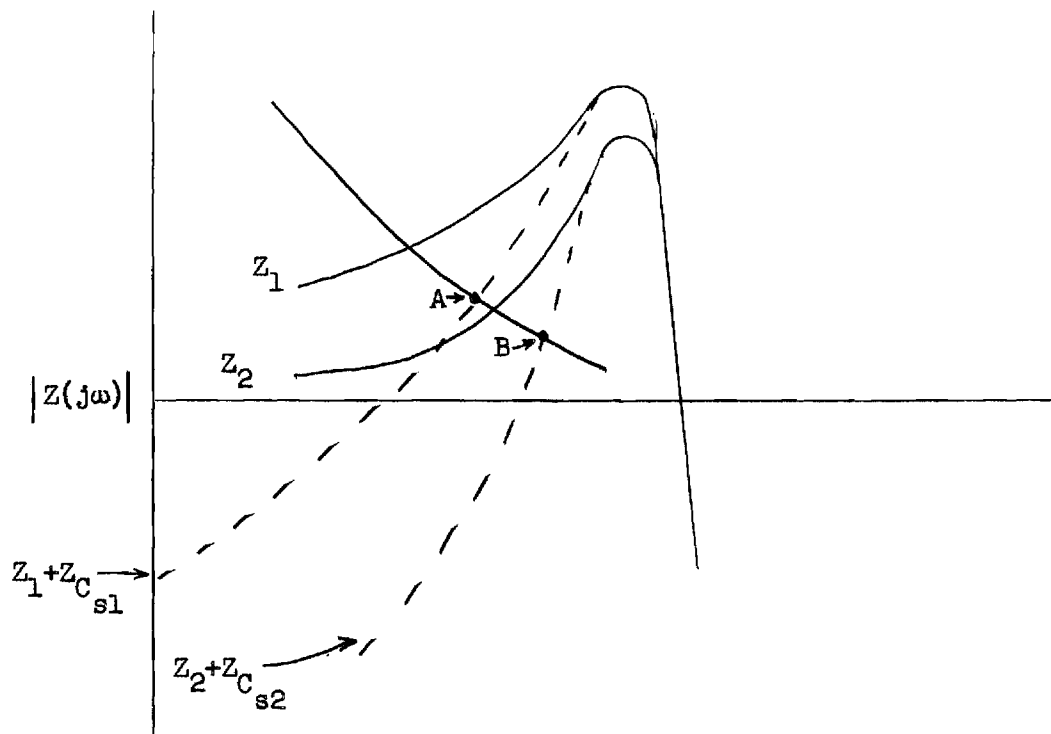


Figure 5.2. Effect of Varying the Cavity Characteristic Impedance.

Ratio Concentric Air Capacitor, manufactured by the Johanson Mfg. Co., is illustrated in a photograph of a completed oscillator and is shown in Figure 5.5. This capacitor permits a variation of capacity from a maximum of approximately 33 mmf to a minimum of 1 mmf. Its one drawback is that it is somewhat temperature-sensitive, although its capacity-versus-temperature characteristics are not specified. The other model utilized is designated as a JFD VC-5 or VC-11, manufactured by the JFD Mfg. Co. Both of these are tubular in design and, most important, are composed of materials with low coefficients of expansivity so that the over-all result is a claimed temperature-coefficient of approximately zero.

The photographs of Figures 5.5 and 5.6 illustrate an oscillator which has demonstrated better orders of frequency stability than have been attained with other similar configurations. Using center conductor B (of Figure 5.3), it operates over the frequency range of approximately 400 to 550 mc. Three curves in Figure 5.7 illustrate certain of its characteristics. The lower

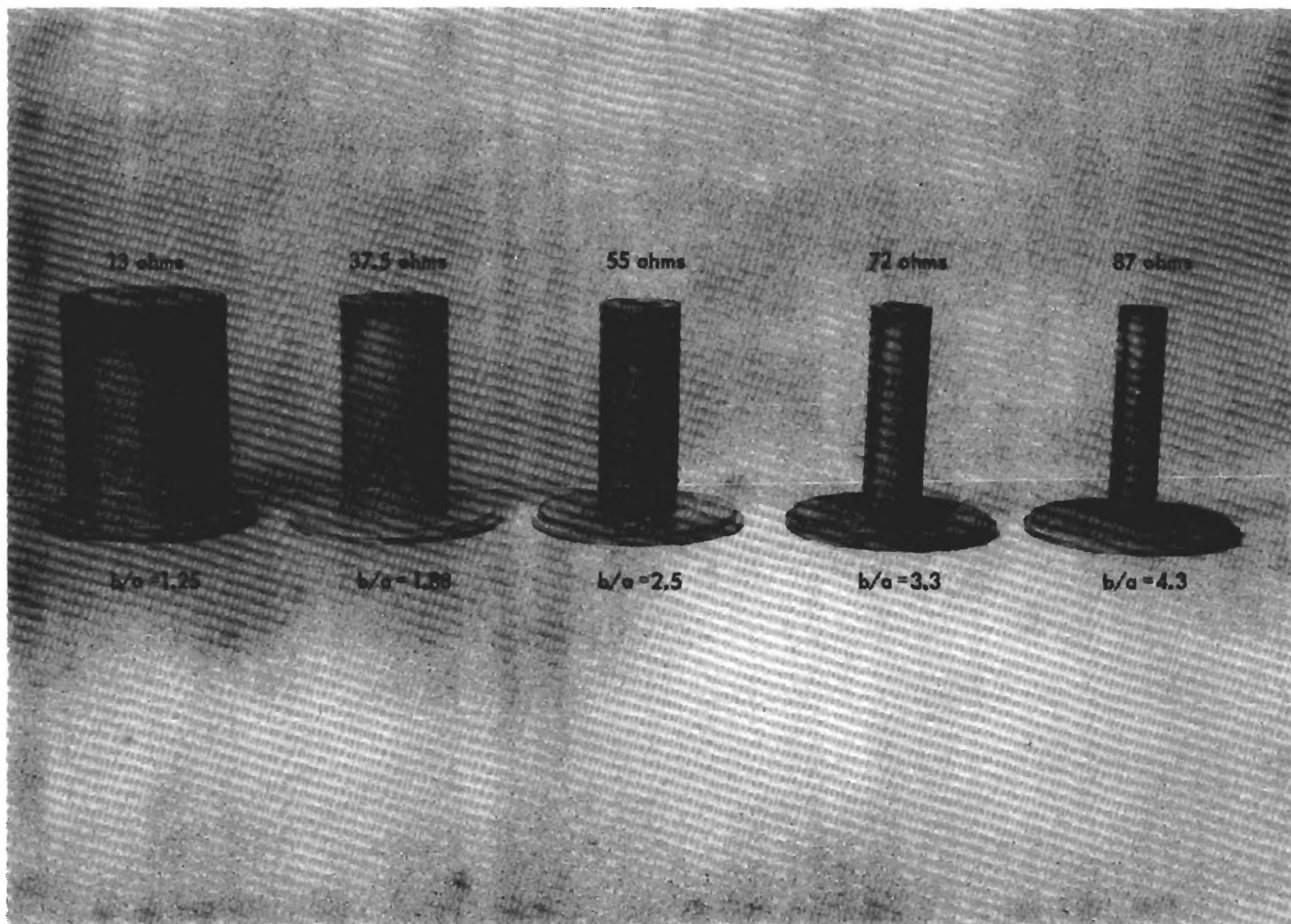


Figure 5.3. Photograph of Series of Center Conductors for Coaxial Cavity.

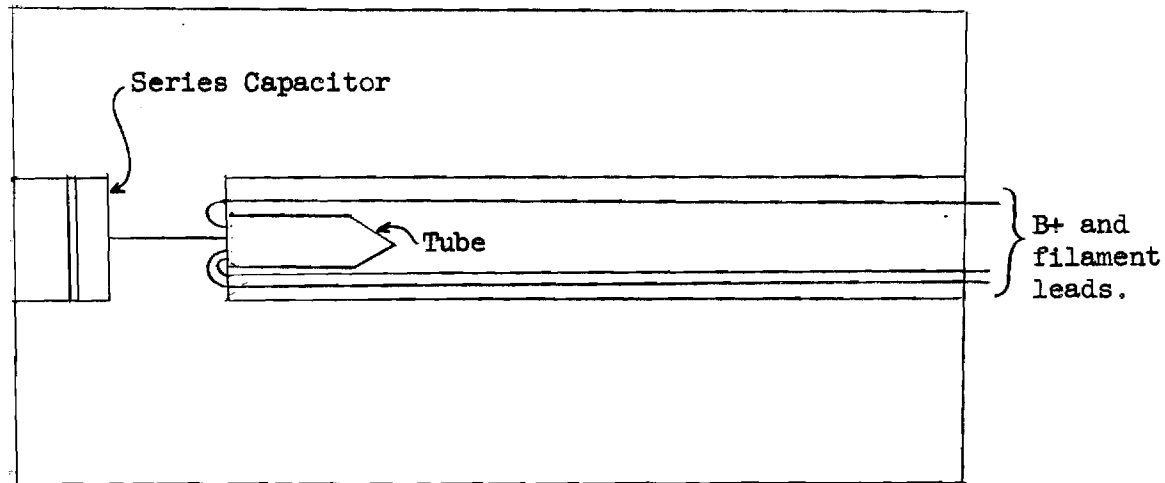


Figure 5.4. Circuit Mounting

curve shows the instability in parts per million per volt change anode potential (ppm/v) when the anode potential was increased from 100 volts to 150 volts. The center curve depicts the frequency drift five and ten minutes, respectively, after setting the oscillator to a new frequency, while the upper figure illustrates the frequency drift when the oscillator is operated from a cold start. It is interesting to note that the known temperature coefficient of brass of about 20 parts per million per degree centigrade would approximately account for the frequency drift experienced in the case of operation from a cold start.

The investigations of the several resonators formed from the center conductors of Figure 5.3 have resulted in data which conform in part to the theories previously advanced relative to the relationship between characteristic impedance, series capacitive-reactance and stability. The use of a cavity with a low characteristic impedance has permitted operation at higher frequencies than is possible with high Z_0 's. This action is illustrated in Figure 5.8, particularly, and to a lesser extent in Figure 5.9. The first of these figures



Figure 5.5. Cavity-Controlled Oscillator, Opened to Show Tube Base and Series-Capacitor.

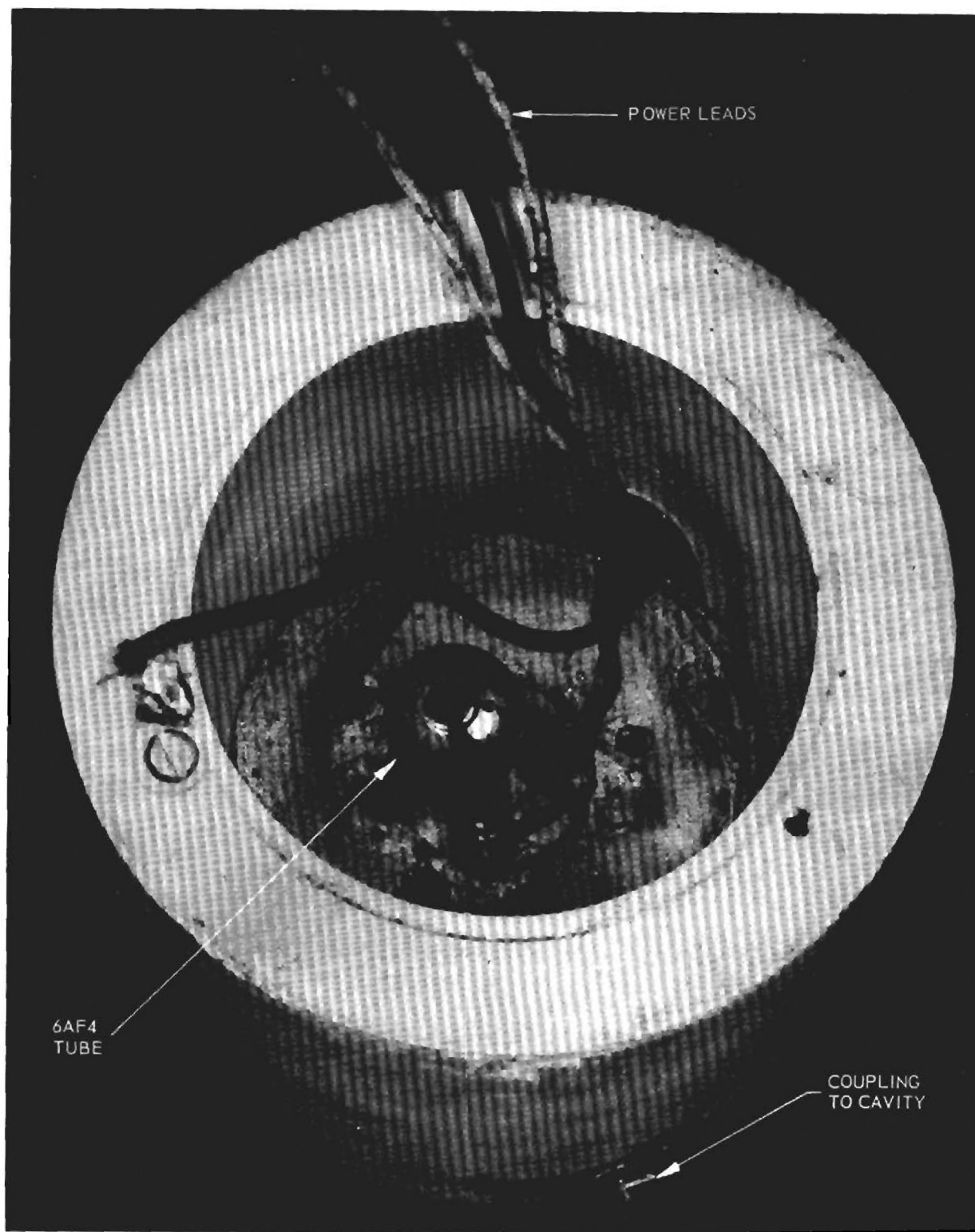


Figure 5.6. Cavity-Controlled Oscillator, Showing Method of Mounting Tube.

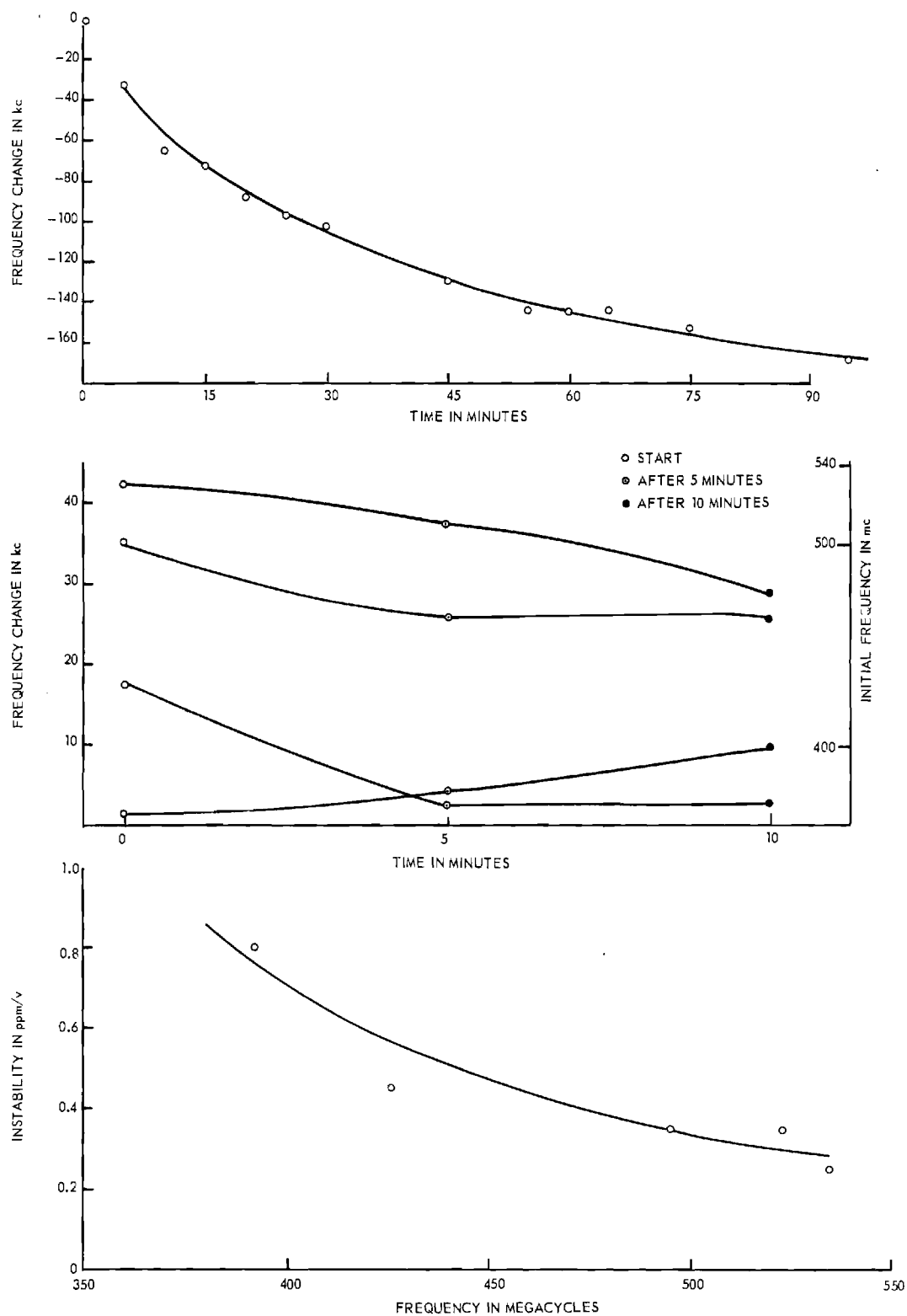


Figure 5.7. Characteristics of Oscillator Shown in Photographs of Figure 5.5 and 5.6.

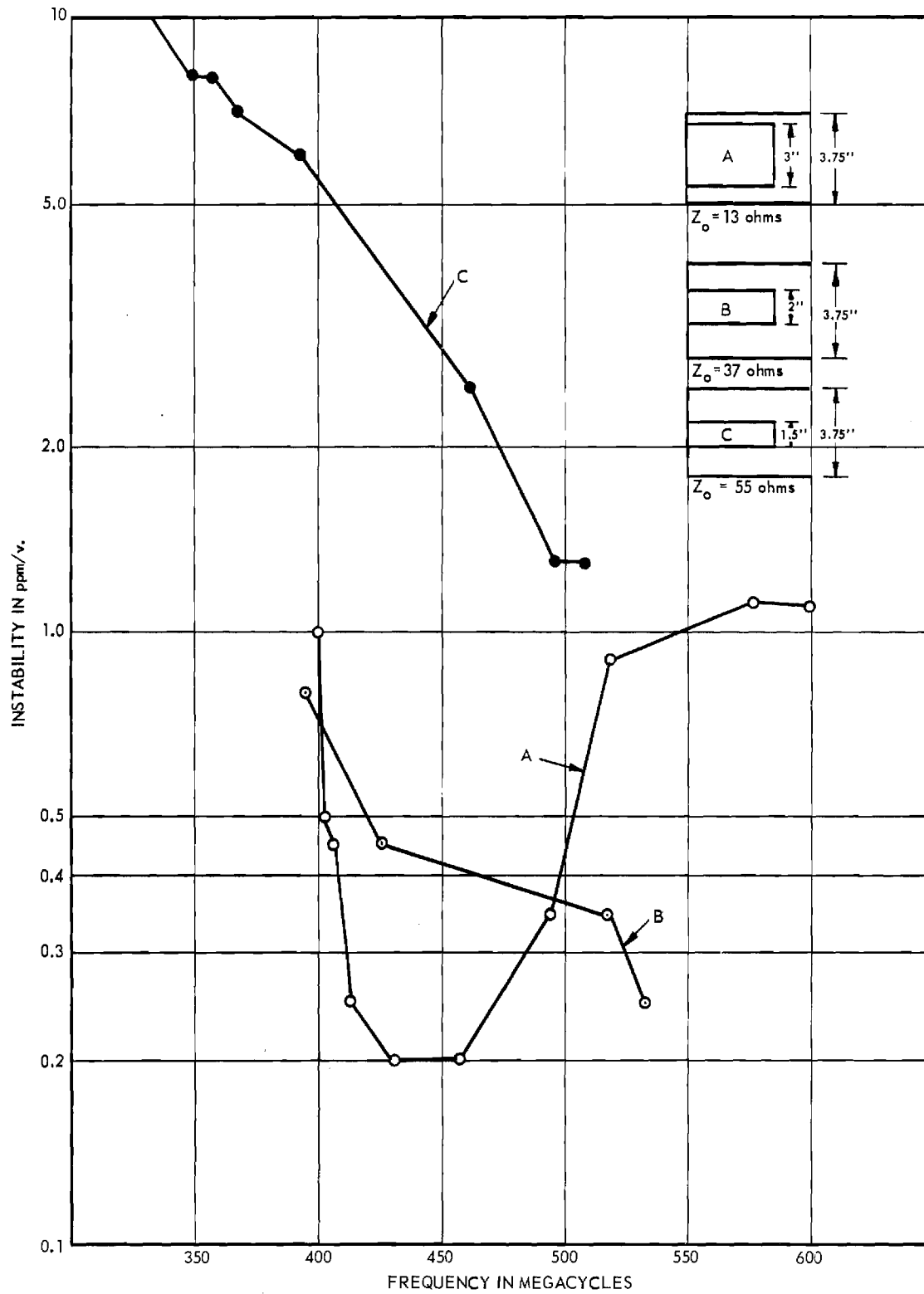


Figure 5.8. Stability Characteristics of Oscillators Controlled by Cavities of Different Z_o 's, Using Tube Type 6AF4.

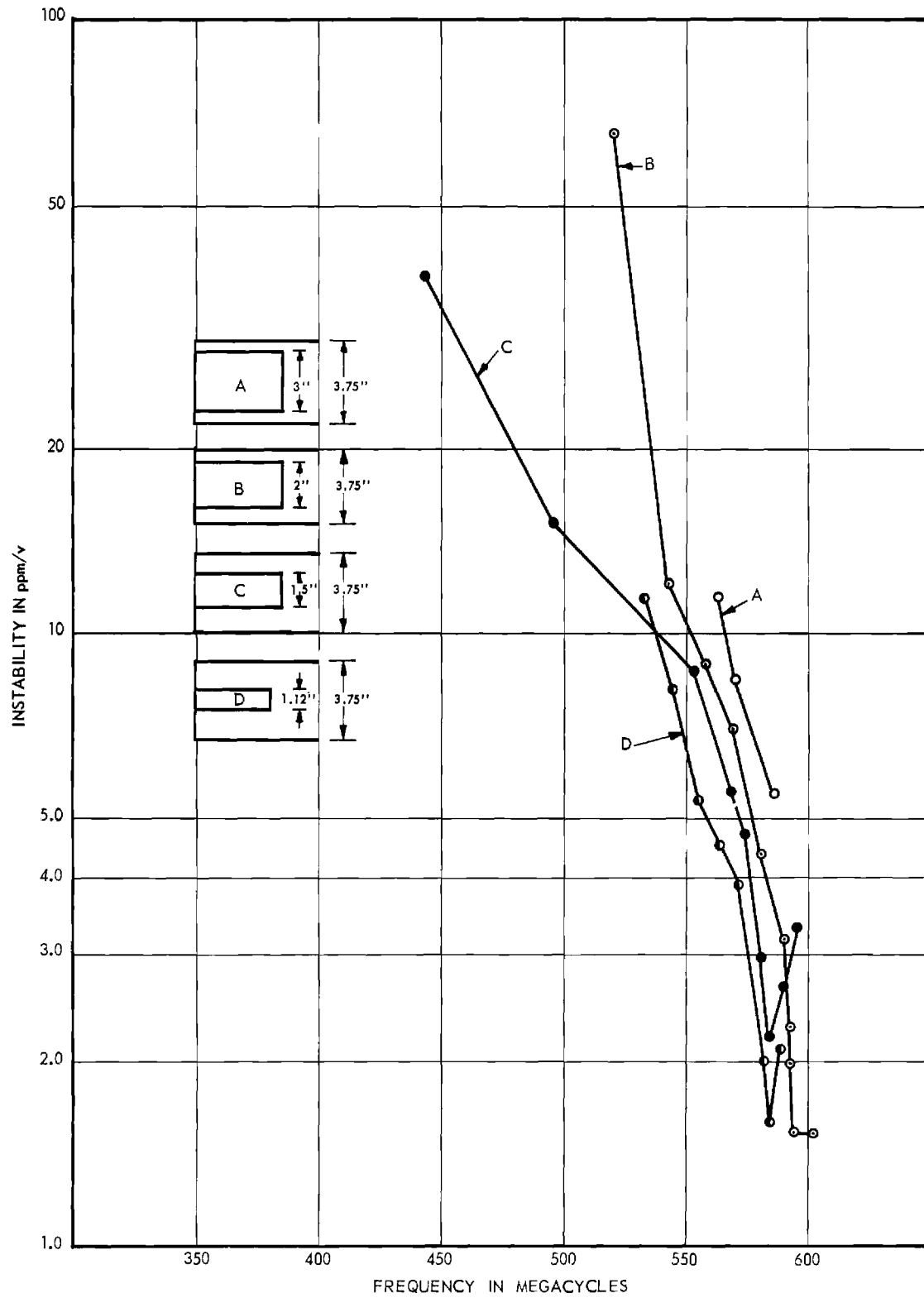


Figure 5.9. Stability Characteristics of Oscillators Controlled by Cavities of Various Z_O 's, Using Tube Type 5718.

illustrates the characteristics of an oscillator when the Z_0 of the cavity is varied, all other parameters remaining constant. Cross sections of the cavities concerned are shown in the upper right-hand corner of the figure. The curves of instability show that instabilities of less than one ppm/v mark the cavities of lower characteristic impedance, but that instabilities of greater than ten ppm/v are observed at the lower frequency end of the high- Z_0 cavity.

Figure 5.9 illustrates the characteristics of similar cavities in which the type 6AF4 tube has been replaced by its subminiature counterpart, the 5718. It will be noted that a common trend is observed for each of the cavities. At the high-frequency end the frequency stability is best; as the frequency is lowered the stability decreases logarithmically.

Figure 5.10 illustrates the stability characteristics of similar oscillators which utilize coaxial cavities with outer conductors of smaller diameters. Although a considerably more attractive physical package results from the use of the small outer conductor, it appears to be necessary to accept decreased stability if the smaller package is utilized. Instabilities not greater than one ppm/v have been obtained, as may be observed by reference to Figure 5.10. It was noted in equations 5.1 and 5.2, and in the related discussion, that the Q of a cavity is decreased through reduction of cavity dimensions if the ratio b/a is held constant. Applying this criterion to the oscillators of Figures 5.9 and 5.10, the smaller cavity is found to exhibit a Q which is approximately 30% less than that of the larger cavity. This decrease in Q may well account for the poorer stability of the oscillator in the smaller cavity.

The present discussion of these oscillators should conclude with the remark that a critical item in oscillator design is found in the cathode choke. Marked differences in oscillator output and in stability result from changes in the cathode choke. No specific formula can be given at this time for determination of the proper configuration, but upon conclusion of tests in the frequency ranges presently being investigated it is planned to tabulate applicable data for each of the tube types used.

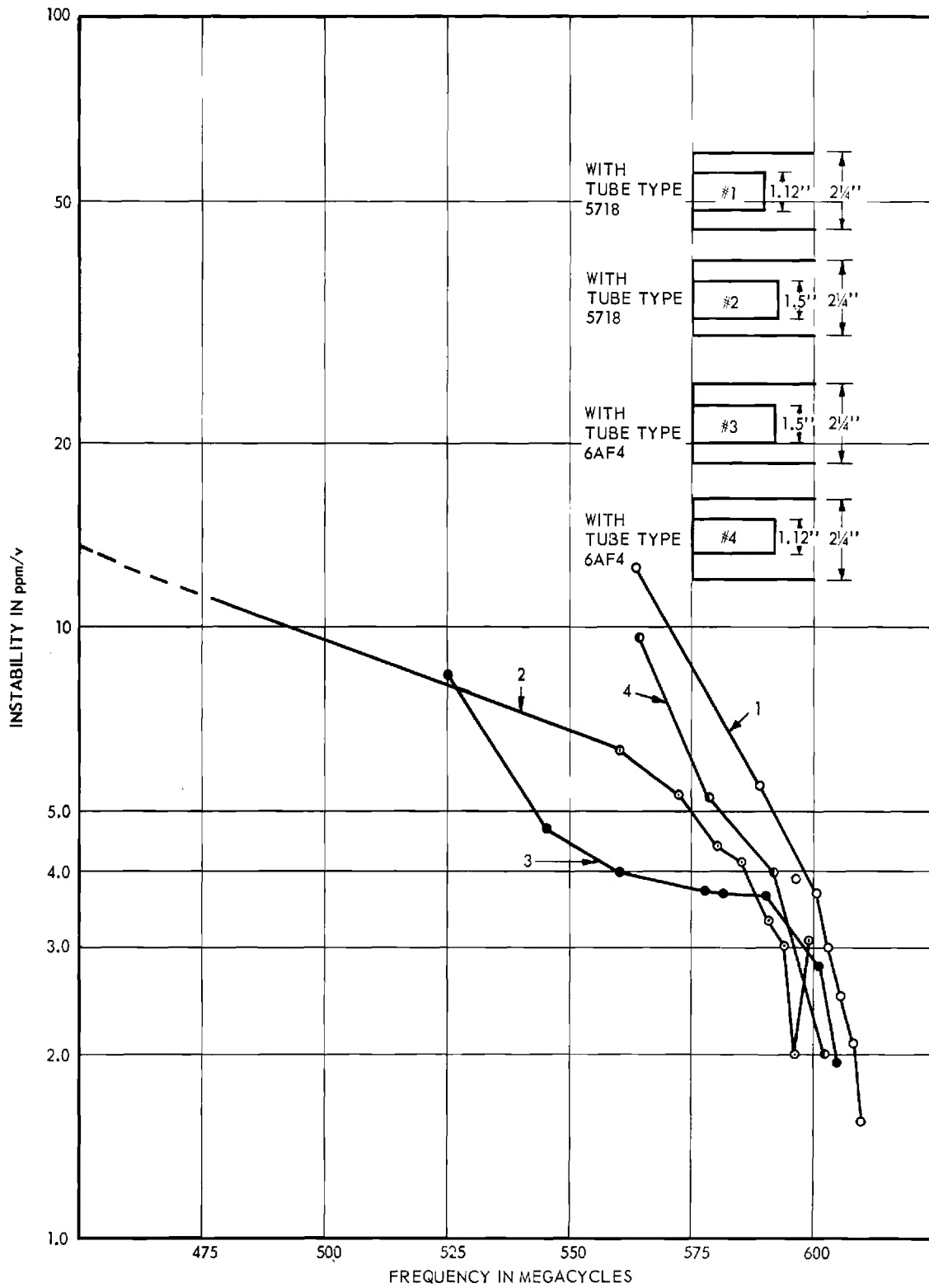


Figure 5.10. Stability Characteristics of Oscillators in Small Cavity.

VI. AUTOMATIC FREQUENCY CONTROL

Some previous work by this project has been directed toward determining simple methods of attaining automatic frequency control at frequencies above 500 mc. In fact, some work was done at lower frequencies (about 200 mc) where it was possible to use the high-order overtone responses of piezoelectric quartz crystals in high-frequency discriminators. It was demonstrated that very steep discriminator slopes could be attained but no simple methods were found to apply these to oscillator control at the frequencies concerned. It is contemplated that further studies of high-frequency discriminator responses may be made at still higher frequencies, provided improved high-frequency crystals are made available.

The problem of controlling the frequency of an oscillator in the frequency region from about 200 to 1000 mc is not easy. The frequencies are too high to permit easy utilization of reactance-tube circuitry and in general too low for use of reflex klystrons.

A very small amount of time has been devoted to this problem during the period of this report. No further studies of discriminator action from quartz crystals have been made, but the closely related action of a cavity resonator in a discriminator circuit has been examined. This latter arrangement has been extended to include two cavities having slightly different resonant frequencies.

The arrangement which was used with a single cavity is illustrated in the sketch of Figure 6.1. The discriminator is shown schematically in the lower part of the figure, the curve of output d-c voltage is shown above. The cavity had a resonant frequency of about 496.1 mc. It will be noted that with an input of 1 volt rms a voltage swing of about four-tenths of a volt dc results from a frequency variation of about 0.2 mc. This change is of sufficient magnitude to give promise of practical application, and might be improved upon by optimum selection of coupling loops within the cavity.

The selectivity of a discriminator using a cavity as the frequency-sensitive element theoretically can be doubled by making use of a second cavity

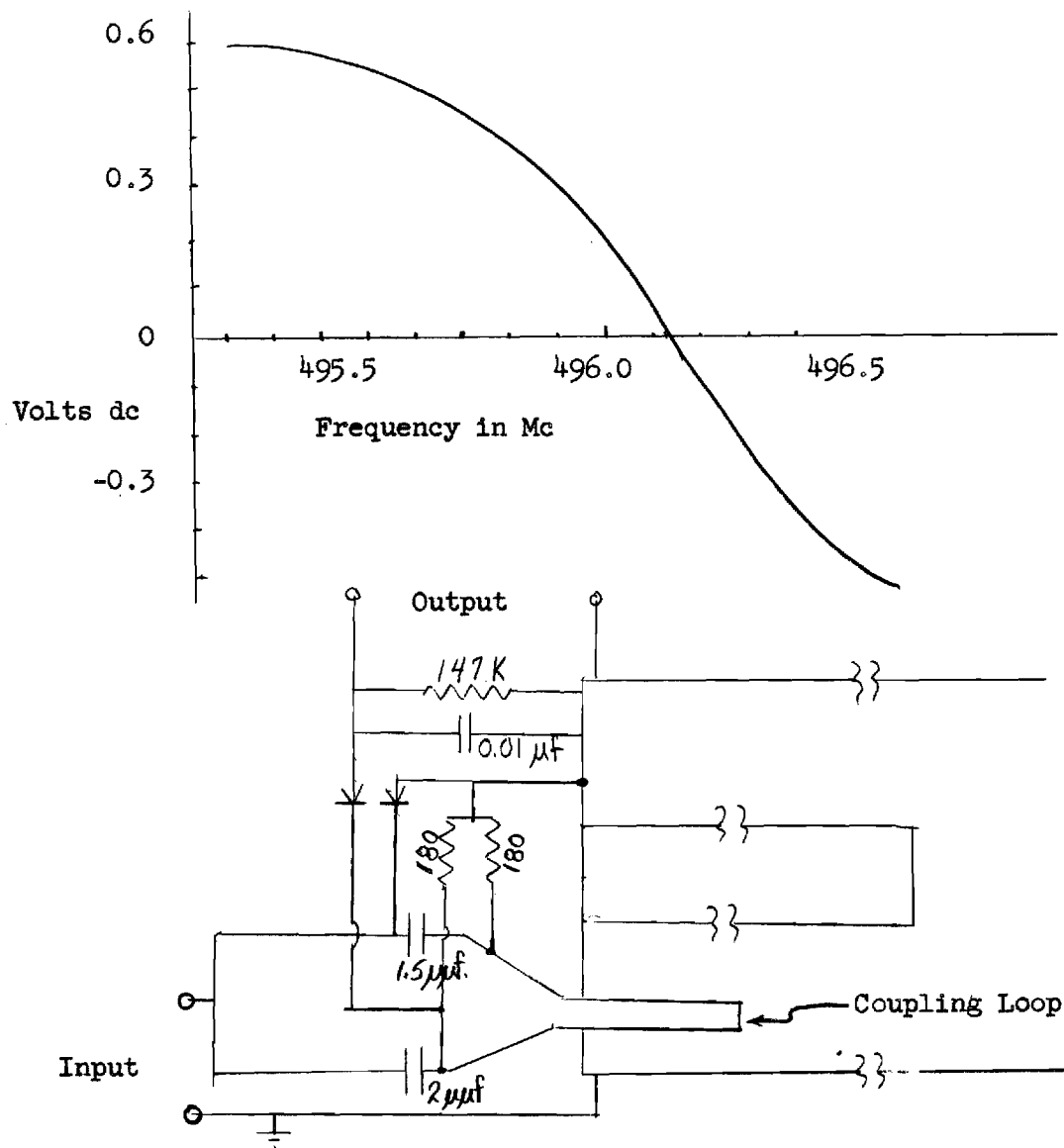


Figure 6.1. Discriminator and Output Utilizing Coaxial Cavity

which has a frequency which is adjusted so that the upper half-power frequency of one coincides with the lower half-power frequency of the other. In this case, if the discriminator is arranged to measure a d-c output which is the difference of the rectified outputs of the cavities then the action will be as illustrated in Figure 6.2.

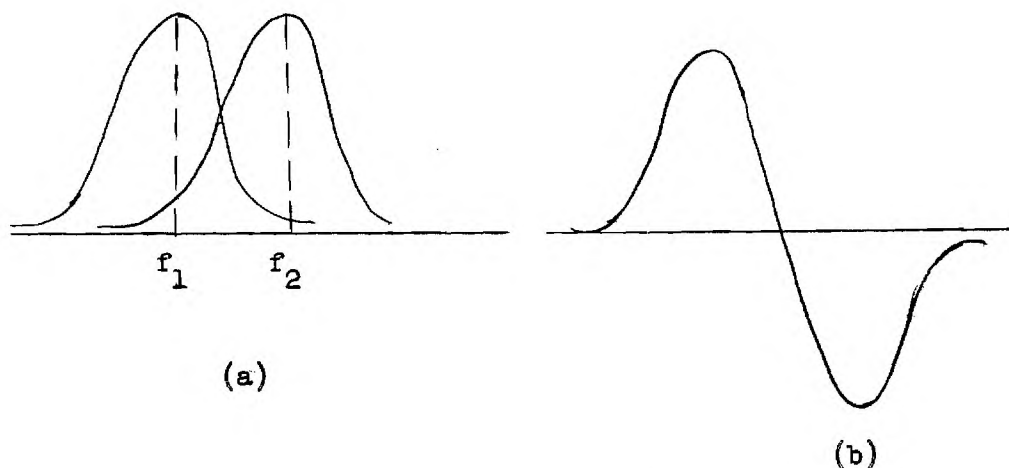


Figure 6.2. Double-Cavity Discriminator Action

This arrangement has also been examined briefly. Indications are that results conform closely to theory. However, difficulty has been experienced in adjusting the tuning of the cavities to the necessary accuracy required to insure the cross-over at the half-power frequencies. The tunable cavity described in section IV of this report has been utilized and, although reasonably small frequency variations can be controlled by the tuning device, it is evident that a vernier device will be required in order to effect a reasonable facsimile of the idealized curve of Figure 6.2. Continued work on this experiment will be undertaken, including adoption of some form of vernier device by the use of which theoretical conditions may be achieved.

The present discussion of automatic frequency control is terminated with a remark that it has been demonstrated that the reflex klystron, a natural tool in AFC because of its frequency-versus-repeller-voltage characteristics, will apparently operate at frequencies well below those listed by the manufacturers. For example, a type 2K28 reflex klystron, considered as usable

only at frequencies above 1000 mc, was furnished with a lower frequency cavity. When so equipped, it was found that the 2K28 operated, with no evidence of undue instability, at frequencies slightly above 600 mc. This oscillator should provide a convenient method for testing discriminators in this frequency range.

VII. CONCLUSIONS

If a coaxial cavity is to be essentially insensitive to variations in ambient temperature, it appears that considerable care must be devoted not only to the materials utilized but also to the method of mounting and of securing the various components that go to make up the cavity. Experiments to date indicate that the preferred method involves the floating of a spring-loaded center conductor in spring-contact fingers. Satisfactory electrical contact is thus secured but flexural stresses are not transmitted from outer to inner conductor.

Hermetic sealing is required in cavities in order to eliminate the effect of changes of humidity within the spaces of the cavity. Sealing can be maintained in a temperature-compensated, tunable coaxial cavity by utilization of small bellows. By use of this component axial motion of the center conductor is permitted without allowing mechanical penetration of the hermetic seal.

Oscillators using coaxial cavities as frequency-determining elements find attractive configurations, from standpoints of both mechanical and frequency stability, in a form wherein the tube is internal to the cavity and is in series with a small capacitor. Stabilities of better than one ppm/v can be achieved, but the oscillator is sensitive to cavity Q and critical to the size and spacing of its cathode choke. Since cavity Q decreases with decrease of cavity dimensions, some sacrifice of stability may be required in order to realize a desirably small unit package.

Automatic frequency control by direct discriminator action appears to be feasible in the 500-1000-mc region, but frequency control of oscillators using conventional triodes is at present not conveniently achieved with d-c voltages. Application of reflex klystrons to this frequency range simplifies the means of obtaining automatic control of frequency.

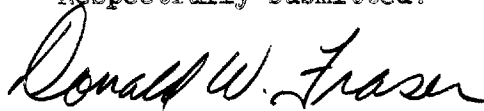
VIII. PROGRAM FOR THE NEXT QUARTER

Primary attention will be devoted to oscillators. The tuned series capacitor and stabilized cavity-controlled oscillator will be further investigated, particularly at frequencies in the neighborhood of 1000 mc using conventional UHF triodes. Pencil triodes will then be tested in efforts to extend the frequency range above 1000 mc.

The investigation of cavities will be continued, particularly to complete an oscillator assembly of the type described above, whose stability will be unaffected by variations of ambient temperature. The fabrication of complete resonators from Invar or fused quartz will be considered and construction may be initiated.

Methods of frequency control by synchronization and/or discriminator action will be investigated. Further study of the high-frequency response of quartz crystals in VHF discriminators may be conducted, dependent upon the availability of suitable crystals. Complete systems employing automatic frequency control will be considered, particularly with the aim of utilizing coaxial cavities therein as frequency-determining elements.

Respectfully submitted:

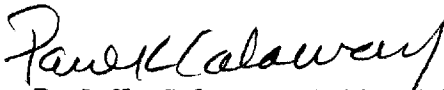


Donald W. Fraser
Project Director

Approved:



J. E. Boyd, Head
Physics Division



Paul K. Calaway, Acting Director
Engineering Experiment Station

IX. IDENTIFICATION OF KEY TECHNICIANS

This project is under the direction of Mr. Donald W. Fraser who devotes one-third time to this work at present. He is Assistant Professor of Electrical Engineering at Georgia Tech and holds the degree of Master of Science in Electrical Engineering from this institution. He has worked on Station Project No. 131-45, "High Frequency Crystal Controlled Oscillators," devoting approximately one-fourth time to it. His other experience includes five years of electronic testing and research in the U. S. Navy.

Mr. James C. Sellers joined the project as Electronics Technician at its onset. He is currently devoting full time to the project. Mr. Sellers previously was engaged for eight years in nuclear instrumentation with the AEC at Oak Ridge, Tennessee, where he had extensive experience as a technician in the design, assembly and testing of electronic circuits.

Mr. James C. Hogg, Jr., Assistant Research Professor, devotes approximately one-third time to the project. Mr. Hogg holds the degree of Master of Science in Electrical Engineering from the Georgia Institute of Technology. Mr. Hogg has had extensive experience in circuit design and oscillators, both in the industrial and the research field. He was employed on a full-time basis on the S.C.E.L. projects, "High Frequency Crystal Controlled Oscillator Circuits" and "Investigation of Frequency Control Above 150 Mc."

Mr. Edward G. Holmes has recently joined the project. Mr. Holmes holds the degree of Master of Science in Electrical Engineering. His experience in the electronics field includes three years of work with frequency-measuring apparatus and broadcasting equipment, two years as Electronics Officer in the U. S. Navy and three years of research and development work in UHF and microwave equipment. He is now devoting approximately one-half time to the project and plans to increase this to full time in the next several months.

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ENGINEERING EXPERIMENT STATION
of the Georgia Institute of Technology
Atlanta, Georgia

PROGRESS REPORT NO. 6

PROJECT NO. 229-198

PRECISION FREQUENCY CONTROL TECHNIQUES
(500 mc and Higher)

By

DONALD W. FRASER AND
EDWARD G. HOLMES

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CONTRACT NO. DA-36-039-sc-42590

DEPARTMENT OF THE ARMY PROJECT: 3-99-11-022
SIGNAL CORPS PROJECT: 33-142B

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MAY 1, 1954 to AUGUST 1, 1954

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I. PURPOSE

The purpose of this project is threefold: (a) to continue work on stabilization of oscillators between 500 and 3,000 mc, using cavity resonators, (b) to continue work on frequency control utilizing high-order overtones of quartz-crystal blanks and (c) to undertake any other investigations which may arise during the course of the work outlined in (a) and (b) above, or which may be mutually agreed upon between the Contractor and the Contracting Officer or his representative.

By agreement with the sponsor, investigations of resonances below 500 mc may be prosecuted as preliminary steps in determining the feasibility of frequency control by the phenomena under study. In addition, cavity resonators previously under construction, and designed to provide control of frequencies below 500 mc, may be completed and tested as aids in perfecting measurement techniques which will later be applied to the range of frequencies above 500 mc.

II. ABSTRACT

During the period of this report, continued efforts have been directed toward improvement of series-capacitor cavity-controlled oscillators. Three hermetically sealed assemblies of this type have been constructed. Each of these three oscillators has a nominal center frequency of 600 megacycles but may be tuned over an approximate 60-megacycle band by adjusting the series capacitor. Two of the three employ type 6AF4 UHF triodes, are identical in type and form but differ in material of which the cavity proper is constructed. One cavity is composed of brass, the other of Invar. Both oscillators have been given preliminary tests to determine their stability characteristics and the results are considered encouraging.

The third oscillator employs a type 5876 pencil triode. It has demonstrated such unsatisfactory stability characteristics in the series-capacity-controlled oscillator that investigations are being discontinued in favor of a re-entrant type of cavity-controlled arrangement. The configuration referred to comprises the equivalent of two quarter-wave coaxial cavities joined end-on by the pencil triode, with a grid-plane iris controlling the plate-to-grid coupling and the plate-to-cathode feedback. The two models of this type construction have also demonstrated encouraging stability characteristics at frequencies of 600 and 800 megacycles, respectively.

Some consideration has been given to the practicability of stabilizing oscillators by synchronization processes, and limited tests have been conducted in the UHF region. It has been demonstrated that synchronization of conventional UHF oscillators is feasible at frequencies up to 800 megacycles using either the fundamental, second harmonic or third harmonic of the synchronizing voltage. It has also been demonstrated that oscillators may be synchronized with interrupted wave-trains as well as with c-w signals.

In the field of automatic frequency control a reactance-tube oscillator combination using a half-wave coaxial cable as a tank circuit shows promise of extending the frequency range of conventional reactance tubes into the upper VHF region. Frequency variations of ten megacycles or more have been observed in an oscillator whose nominal center frequency is 200 megacycles.

III. SERIES-TUNED CAVITY-CONTROLLED OSCILLATORS

The previous two progress reports (1,2) contained a discussion of the theoretical aspects of a cavity-controlled oscillator which utilized a small capacitor in series with the cavity's center conductor. Arguments were advanced to show that the addition of series capacitive reactance steepened the slope of the reactance-versus-frequency curve of the frequency-determining element. The increased slope, it was shown, should provide a theoretical improvement in the frequency stability of any cavity. In addition, it was shown that the composite reactance curve should be modified by a variation of the characteristic impedance of the cavity.

A number of tests were reported upon which illustrated these points. The results of these tests show that a considerable improvement in the frequency stability of a cavity-controlled oscillator could be achieved by the expedient addition of a very small capacitor in series with the center conductor of the cavity. Similar tests were concerned with the effect of a variation of the characteristic impedance of the coaxial cavity upon stability. The results of these latter tests were not completely conclusive but did demonstrate that a near optimum in stability was found in a cavity which had large outer dimensions and a medium characteristic impedance. In addition, the type of tube utilized was shown to influence greatly the over-all stability of the assembly.

During the period of the present report the information previously gained was applied to the construction of several oscillators in the 600-mc region. Two of these are essentially identical, differing only in the material of construction. One is composed of brass, the other is completely constructed of Invar. The two oscillators have been compared under constant-temperature tests one against the other and have exhibited little variation in relative frequency during periods of not less than one hour. Variations of frequency of the Invar cavity oscillator during changing temperatures have not as yet been determined, since presently available frequency-measuring equipment has proved inadequate in the test. New measuring equipment, now being procured, shows promise of permitting accurate determination of the long-term stability characteristics of both of these oscillators.

A third series-capacitor cavity-controlled oscillator has been constructed, this one utilizing a type 5876 pencil triode. In this arrangement the problems of providing proper support for the tube have proved to be difficult, a situation resulting in several fractures of glass-to-metal seal within the triode. The stability of the associated oscillator has proved, in addition, to be considerably poorer than that of any of those comparable oscillators which utilize conventional UHF triodes.

A completely different arrangement for the pencil triode oscillator obviates many of the difficulties mentioned above. One form which has been devised is described in detail in another section of this report. The pencil triode has the distinct advantage of having a considerably higher upper frequency limit than the conventional UHF triodes have. The type 5876 has been tested in numerous oscillator arrangements approaching 1000 megacycles, and no frequency-limited tendencies have been observed. On the other hand, the series-capacitor cavity-controlled oscillator using the type 6AF4 has not been operated at frequencies above 700 megacycles. This latter figure appears to be an upper limit for the configuration discussed in this and previous reports (1,2).

A. Tunable Series-Capacitor Oscillators at 600 Megacycles

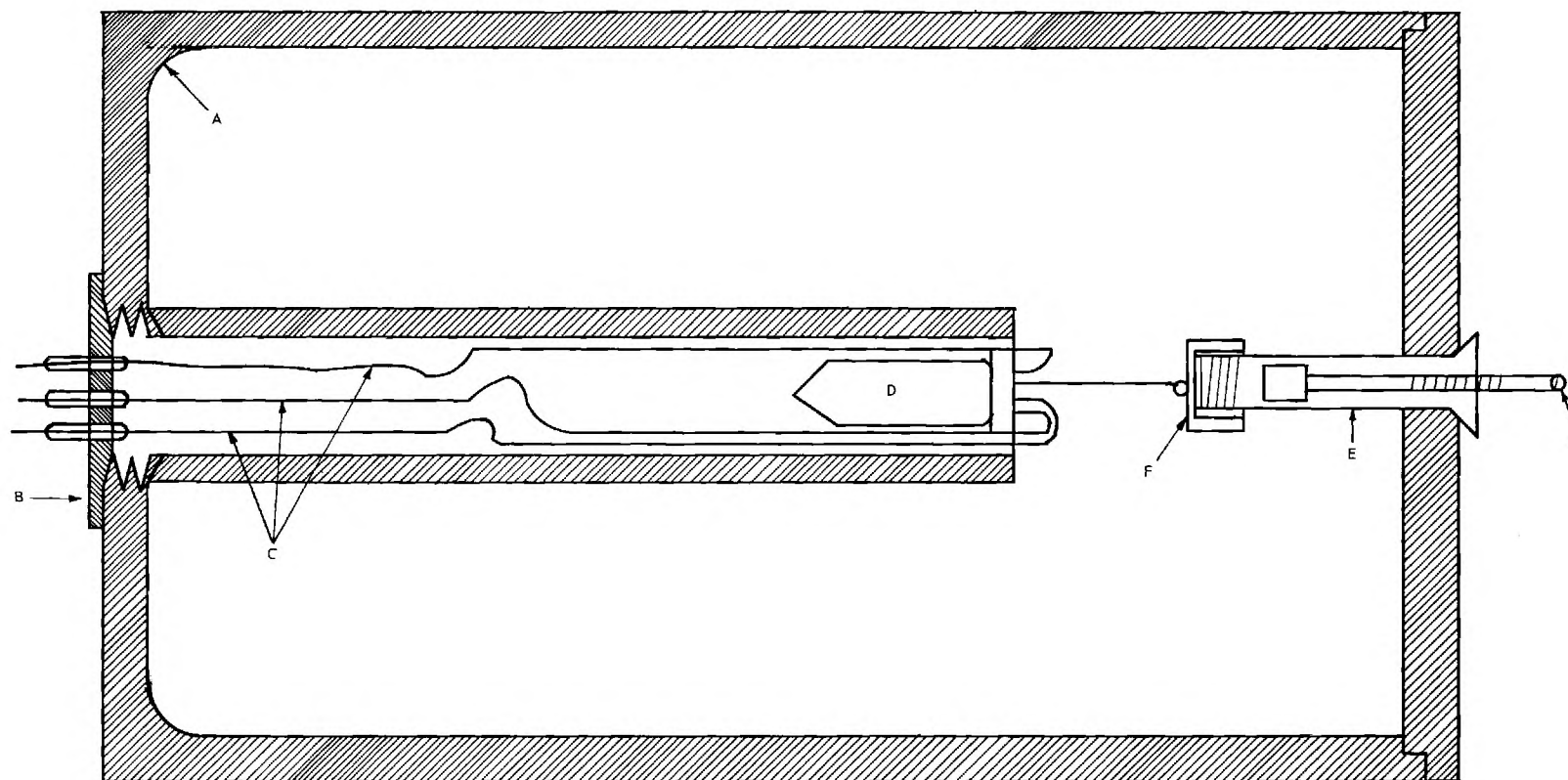
The capabilities and possibilities of series-capacitor oscillators with tubes mounted internally to a coaxial cavity have been well demonstrated by tests previously reported (2). It was henceforth decided to construct such a cavity-controlled oscillator which should center at 600 megacycles and tune over a moderate range of 40 to 50 megacycles. The design selected was to represent a near optimum in frequency stability but might exhibit compromises affecting form factor, materials utilized and method of construction. One such obvious compromise is illustrated by the fact that best stability is exhibited by a coaxial cavity whose diameter of outer conductor is such as to render the resulting configuration unreasonably massive. Hence, a smaller-than-optimum cavity diameter was selected with a theoretical small sacrifice in stability. Another compromise is indicated in the materials and method of construction. For example, it has been shown that the best frequency-versus-temperature characteristics are found in coaxial

cavities employing temperature-compensation techniques. Compensated cavities have, however, normally contained a center conductor having a glass or a ceramic base. These materials are obviously not well suited to serve as mounts for oscillator assemblies. On the other hand, the utilization of a metal of low expansivity results in a firm mechanical design but gives reduced stability with respect to temperature.

The form and some details of the configuration selected are illustrated in Figure 3.1. The outer diameter of the cavity was chosen to be three inches in order to provide a satisfactory form factor and at the same time sacrifice little in stability characteristics.

Hermetic sealing is required in cavity resonators to improve the Q by elimination of water vapor and to promote frequency stability by removing the humidity variable. Sealing is provided in this resonator at one end by inserting a hermetically sealed socket within the center conductor. Electrical connection to the power leads are made through this seal, as illustrated in Figure 3.1. Sealing at the other end is effected by modifying the variable capacitor located there. In the oscillator of the same figure, a capacitor type JFD VC-5, manufactured by the JFD Mfg. Co., having a claimed temperature coefficient of approximately zero, connects the plate of the tube to the end plate of the cavity. The capacitor has a cylindrical shell which is normally open at one terminal. In order to seal this cylinder, it was provided with a shaped cap in the form of a thin Invar shell. This cap is then forced over the open end of the cylindrical capacitor and complete sealing is then effected by running sufficient solder into the cap in order to provide a firm union between cylinder and Invar cap.

The outer conductor and high-current (shorted) end of the coaxial cavity are formed from a single piece of Invar. This form was obtained by boring a three-inch rod of Invar, terminating the cut as shown to leave a rounded shoulder at the closed end. That end was then drilled and tapped in preparation for the insertion of the center conductor. The latter is assured good electrical continuity and mechanical stability by a slight undercut along the contacting face, as illustrated in the figure.



- A. SINGLE PIECE OUTER CONDUCTOR
- B. HERMETIC SEAL AND POWER-SUPPLY FEED-THROUGH
- C. POWER LEADS
- D. TUBE TYPE 6AF4
- E. CAPACITOR, TYPE JFD VC-5
- F. INVAR CAP FOR HERMETIC SEAL
- G. TUNING CONTROL

Figure 3.1. Details of Invar-Cavity Oscillator.

Two models of this oscillator were constructed, the first a prototype of brass and the second a finished model of Invar. A photograph of such a completed cavity is shown in Figure 3.2.

Preliminary short-term tests indicated that the stabilities of the two oscillators were essentially identical, therefore plans were made to initiate tests to determine their long-term stability. It has been previously mentioned that the frequency standard utilized in determining short-term stability is a Gertsch FM-3 frequency meter. This instrument has a claimed accuracy of ten parts per million, sufficient for short-term tests but clearly of insufficient accuracy for long-term tests. In order to provide a more accurate device, consideration was given to modification of the same frequency meter. However attempts to modify the instrument by injecting an external signal in place of the internal oscillator failed. This failure was caused by the presence of unwanted frequency modulation in the "standard," modulation of sufficient magnitude to distort seriously the higher harmonics required to measure frequencies in the vicinity of 600 megacycles.

The determination of long-term stability not being determinable by direct means, a comparison method was attempted next. The two oscillators, supplied by separate sources, were first tuned until their frequency separation was a few hundred cycles. This audio frequency was then converted into a corresponding direct voltage, and the result recorded with an Esterline-Angus Recorder. In order to eliminate the probable adverse effects of variations of ambient temperature on the brass cavity, the complete test was conducted in a constant-temperature atmosphere. The results of the tests were not conclusive inasmuch as the frequency difference, after remaining essentially constant for a one-half hour period, deviated from the original reference center frequency in a relatively abrupt manner.

The results of a recording covering several hours is illustrated in Figure 3.3. The essentially constant frequency difference is seen in the first portion of the recording, the mentioned deviation is observed in the other portion. It is interesting to note that the indicated frequency



Figure 3.2. Photograph of Invar-Cavity Oscillator.

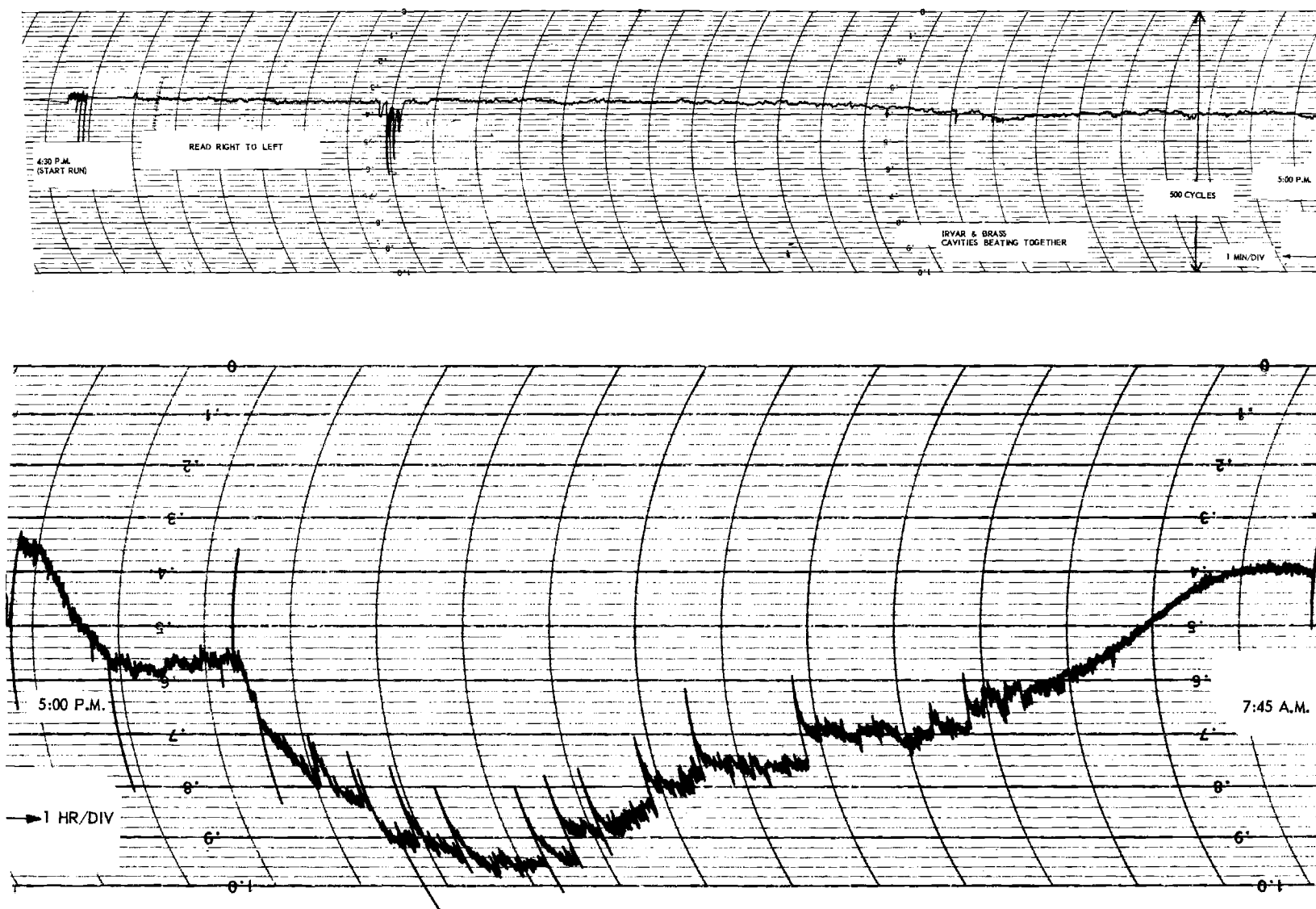


Figure 3.3. Recording of Beat-Frequencies Between Two Cavity-Controlled Oscillators.

stability during the half-hour period was of the order of one part in 10^7 and that over the entire test it was better than a part in 10^6 . Unfortunately this type of test gives no indication of the characteristics of each oscillator alone and can only point a trend rather than lead to definite conclusions.

The problem of determining accurately the frequency characteristics of these oscillators may be solved by the expected early local procurement of a frequency counter. This instrument, counting cycles up to two megacycles, will permit accurate monitoring of the internal oscillators of the FM-3 frequency meter. By this expedient of monitoring it is hoped to obtain accurate data on the two 600-megacycle oscillators mentioned and on other types now under construction. The results will be furnished in a later progress report.

B. Series-Capacitor Oscillator Using Pencil Triode

The pencil triode is well known to exhibit excellent UHF characteristics, particularly in applications as grounded-grid amplifiers. The mechanical structure permits excellent isolation of the plate from the cathode, a condition which lends itself admirably to amplifier application but militates against the tube's performance in conventional UHF oscillator circuits. High-frequency oscillators which use simple two-terminal networks (hairpin loops, cavities, etc.) as frequency-determining elements are usually represented schematically as shown in Figure 3.4.

If C_p is the plate-to-cathode voltage in Figure 3.4, then the grid-to-cathode voltage is given approximately by $V_g = V_p \cdot \frac{C_p}{C_g}$. It is evident from this expression that a tube having a very small plate-to-cathode capacitance is not well suited to direct application in oscillator circuits of the type shown in Figure 3.4 because of the small magnitude of feedback voltage. However, a modification of the feedback conditions may convert the tube and circuit into a satisfactory oscillator. One obvious way is to couple a small pick-up loop to the magnetic field of the frequency-determining element and to inject its voltage, with proper polarity, into the grid or cathode circuit. This expedient was attempted, as explained below, with a type 5876 pencil triode in a coaxial cavity essentially identical to that

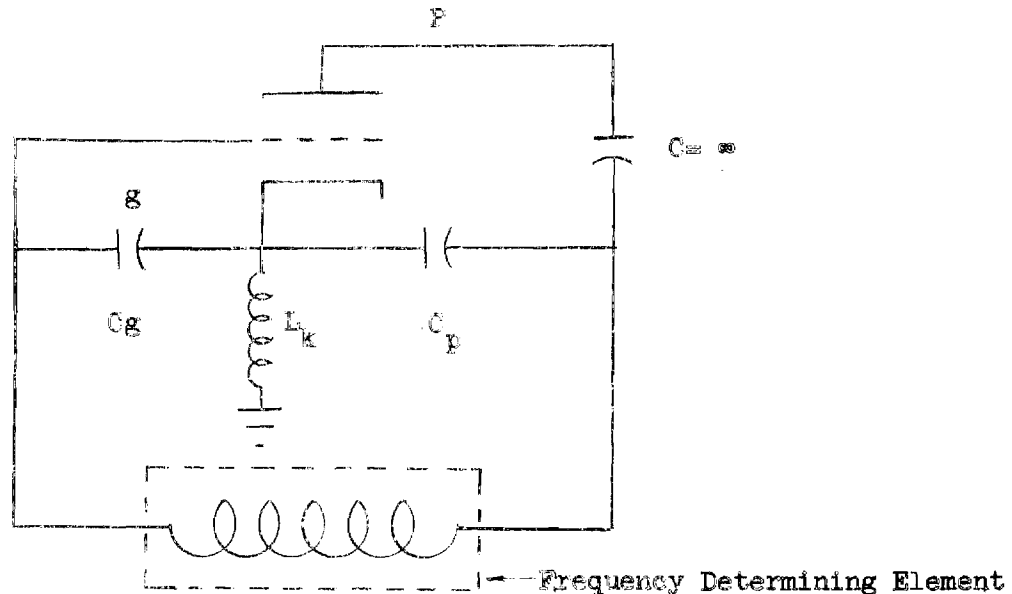


Figure 3.4. A Schematic Representation of a Conventional UHF Oscillator described in the previous pages of this section. The configuration selected is illustrated in Figure 3.5.

This arrangement oscillates very weakly in the absence of some form of added positive feedback. Such added feedback can be provided in the oscillator depicted by the feedback loop. A loop of this form was added to the assembly under discussion and is illustrated in the figure. The feedback energy finds a path to the cathode in the coaxial-type space between the center conductor and an internal tube. This tubing serves also to shield the filament leads from the r-f field of the feedback path. The complete assembly is seen to be a coaxial cavity within a coaxial cavity, the inner grid-to-cathode cavity serving merely for purposes of feedback, the outer one representing the frequency-determining element.

In an early version the feedback loop was omitted. The assembly did oscillate although very weakly, at a frequency of approximately 535 megacycles and with poor stability. The frequency of operation was lower than had been anticipated inasmuch as the coaxial cavity (neglecting effects of the end-piece) had been designed to be resonant at about 725 megacycles. The fact that the assembly oscillated nearly 200 megacycles below theoretical resonance indicates that operation was occurring at a low-impedance

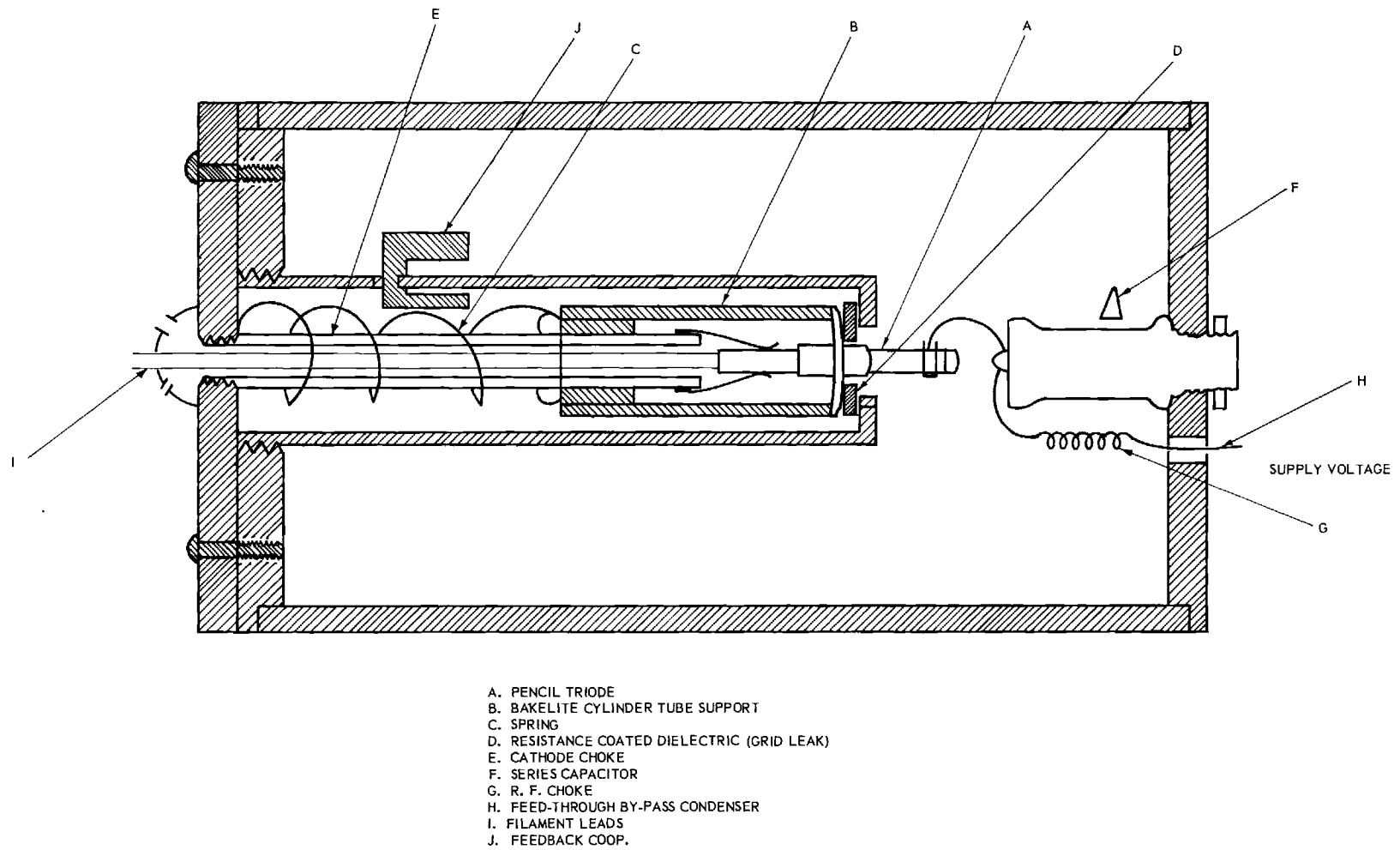


Figure 3.5. Series-Capacitor Cavity-Controlled Oscillator With Pencil Triode.

point in the impedance-versus-frequency characteristic, a point of small slope in the reactance-versus-frequency characteristic. Hence, it might be anticipated that the frequency stability could not be good, a theory borne out by experimental data.

It might be surmised that the addition of considerable positive feedback would move the operating point to a position of higher impedance on the impedance-versus-frequency characteristic, a point of steeper slope and of higher frequency. In fact, in another form of oscillator (described in the next section of this report) such action occurs exactly as predicted. In the one presently under discussion however, there have been disappointingly small changes regardless of the apparent amount of feedback. A slight rise in frequency occurs, accompanied by a slight improvement in frequency stability. The grid drive is considerably increased, but the assembly apparently still fails to operate at a high-impedance point in the impedance-characteristic curve.

The unsatisfactory electrical characteristics are accompanied by rather difficult problems of mechanical support of the pencil triode. This tube has proved to be quite fragile in the glass-to-metal seal at point of contact between the grid ring and the remainder of the tube structure. Fractures of several tubes have occurred in experimental mountings, and a completely satisfactory method of tube support has not been attained in this oscillator. However, the different form of oscillator already mentioned, and described in detail in the next section, incorporates a tube ~~mounting~~ which is believed to offer satisfactory electrical contact without completely rigid mechanical support. It thereby removes the constant hazard of tube breakage.

The observed difficulties with the pencil triode in the series-capacitor coaxial-cavity arrangement, coupled with its observed instability and its tendency toward off-resonance operation, combine to indicate that the described arrangement cannot be designed to provide oscillations of stable nature. Experimental investigations of this form have been discontinued in favor of a re-entrant type which has shown much more promise. It is discussed in detail in the pages immediately following.

IV. RE-ENTRANT CAVITY WITH PENCIL TRIODES

The pencil triode appears to be one of the most attractive tubes for oscillators in the 500- to 1500-mc region. As pointed out in section III, however, the tube was placed in a series-cavity arrangement in which the tube type 6AF4 had produced excellent frequency stability, only to produce results which were rather disappointing. Positive feedback was incorporated to increase the grid drive, but this did not particularly improve the results.

Therefore, it was decided that an arrangement similar to that used in conjunction with the lighthouse tube might be used. Some of these arrangements are shown and discussed in Reich's (3) text. One of these, a form of re-entrant cavity is shown below in Figure 4.1.

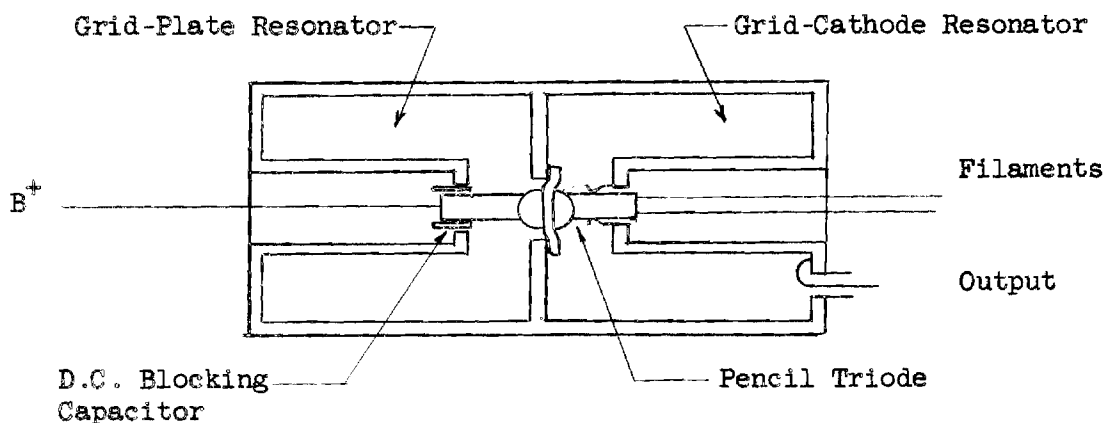


Figure 4.1. Re-entrant Type Cavity Using Pencil Triode

The grid is shown at d-c ground potential in this arrangement. The only source of feedback in this circuit is the plate-to-cathode capacitance, a quantity which is very small in the pencil triode type 5876. The lumped-element equivalent of this circuit is shown in Figure 4.2.

Referring to Figure 4.1, it is seen that energy can be coupled from the plate-grid resonator to the grid-cathode resonator by placing holes in the ring which supports the grid. Following the reasoning set forth in the construction of the series-capacitor type of oscillator arrangement, it was thought that capacitive coupling of the grid to this ring might increase the reactance slope in the manner previously evidenced. This action is described in Progress Reports 4 and 5 (1,2). If the grid signal is to be derived through capacitive coupling, it must have conductive coupling of some sort to the cathode providing a d-c path for grid current. An arrangement which furnishes a-c and d-c continuity is shown schematically in Figure 4.3.

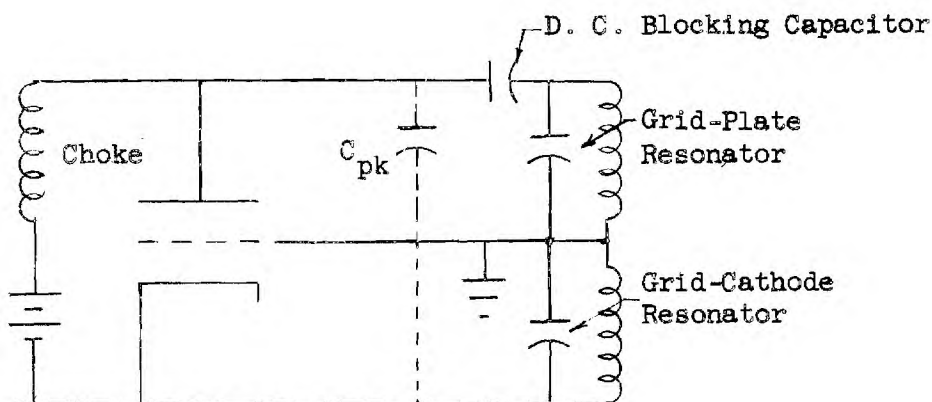


Figure 4.2. Lumped Equivalent of Re-entrant Cavity and Triode.

The tuning screws are used to vary the amount of capacitive coupling to the grid. It can be seen that as the screws are inserted into the cavity, the energy feedback between the two resonator sections will be decreased, since the reduced opening results in a decrease in mutual coupling. The lumped element of the arrangement shown in Figure 4.3 is illustrated in Figure 4.4.

Here the effect of the tuning screws is seen to vary the coupling between the resonators and also to vary the capacitance coupling to the grid. These two effects are, of course, inversely related. That is, as the capacitance is increased, the mutual coupling is decreased.

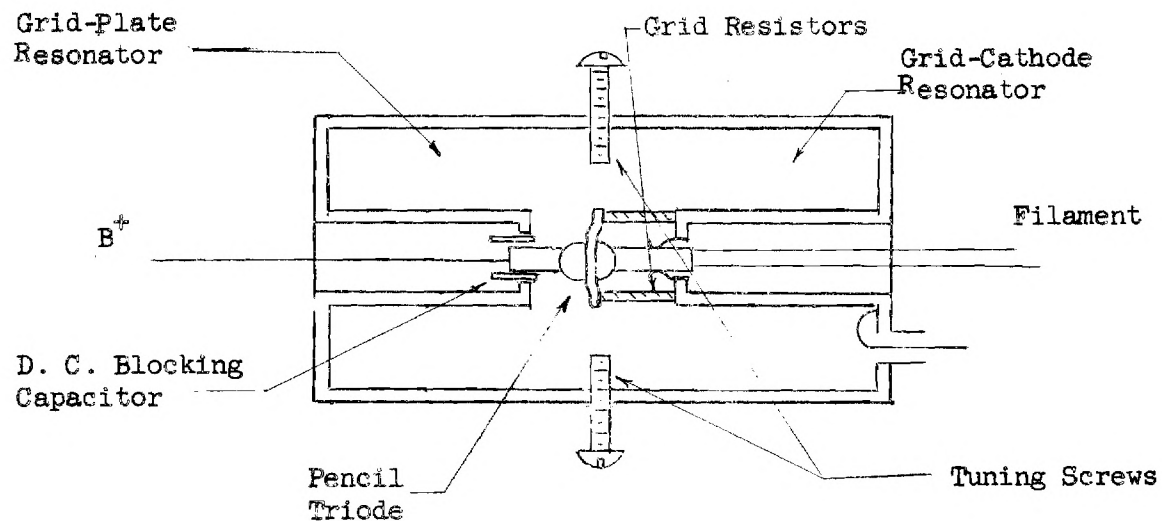


Figure 4.3. Capacitively Coupled Re-entrant Cavity.

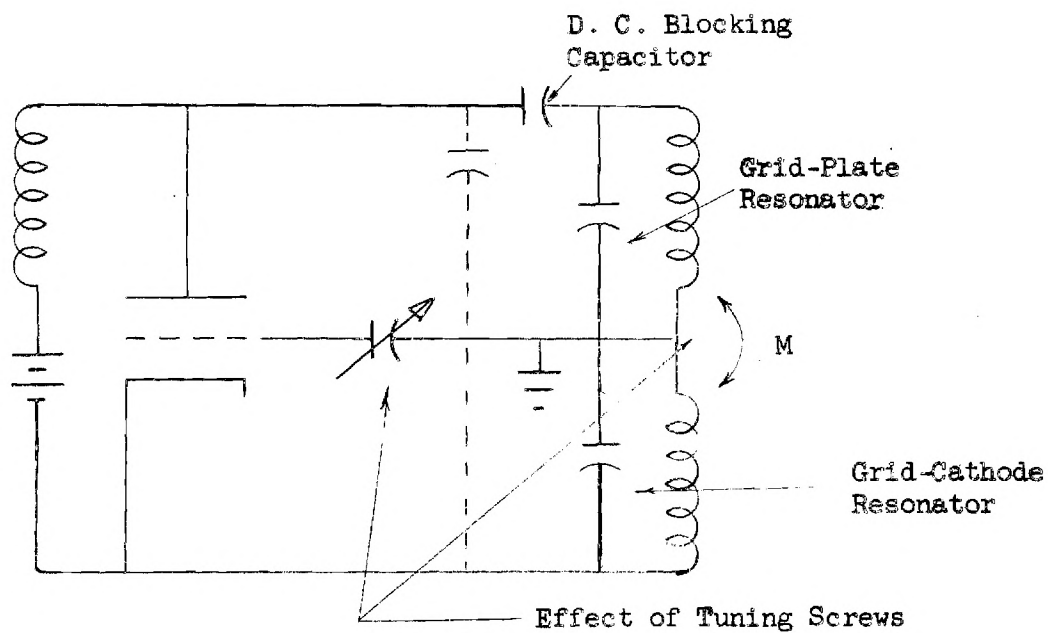


Figure 4.4. Lumped Equivalent of Capacitively Coupled Re-entrant Cavity.

The tuning screws, while capable of fine adjustment, were found to be mechanically unsatisfactory. In place of these tuning screws, various sizes of washers were clamped to the grid. One of the actual models tested is shown in the accompanying photographs, Figures 4.5, 4.6 and 4.7.

In Figure 4.5 these washers, which shall be called irises, are shown in detail. In addition the method in which they are clamped to the grid of the tube is represented. Five discrete sizes of irises were tested, and finally in the last test, the iris was completely removed.

Figure 4.6 shows an exploded view of the oscillator assembly. Parts B and F are the sections of the outer conductor. Parts A and B make up the grid-cathode resonator, while parts F and G make up the plate-grid resonator. Part C is a molded and machined cylinder of Scotch Plasticast serving the purpose of supporting both the pencil triode D and four 4.7K resistors in parallel around the grid structure. One of the irises, part E, is shown. This is also held in place on part C and serves the additional purpose of holding the tube in place. Part H is inserted into G and serves as conductor for the plate supply voltage. A small ceramic washer on the left end serves as a by-pass condenser of 75 mmfd capacity. Another by-pass condenser in the form of a feed-through is seen on the right end of the picture. Part I is a spring which exerts pressure on H so that the ceramic washer will make good contact on the inside of G. Finally part J serves to support the right end of H and to maintain pressure on the spring. A semi-assembled view of the arrangement is shown in Figure 4.7.

A cross section of the assembled oscillator with dimensions, is shown in Figure 4.8. As before, the section on the left of the drawing is the cathode-grid resonator, while that on the right is the plate-grid resonator. The construction was designed in this way to permit the tuning screws to be placed in the coupling sleeve. A more important reason, however, was for ease of assembly and disassembly. This particular oscillator operated at a maximum frequency of 650 megacycles.

It was previously mentioned in section III that the pencil triode is a very delicate tube type and is easily broken. For this reason accurate alignment of supports is required. The dimensions on this sketch are shown

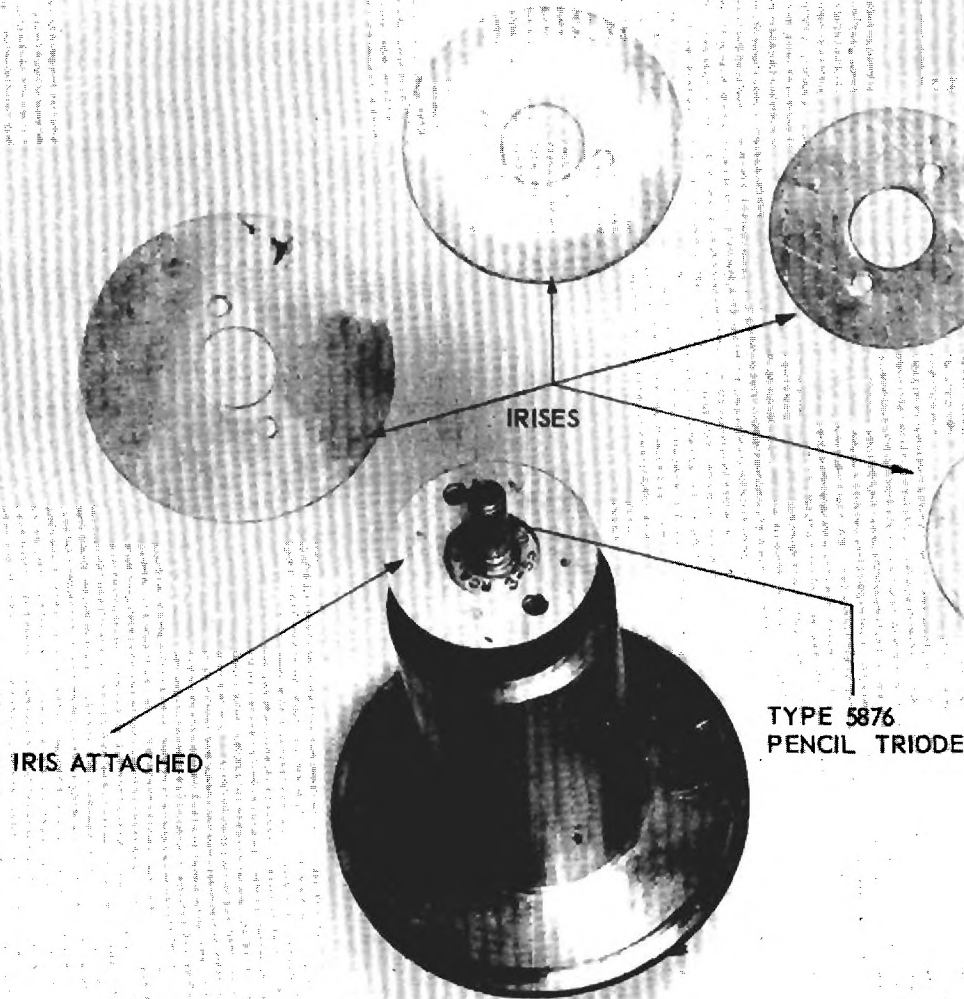


Figure 4.5. View of Iris Sizes and Grid Connection in Re-entrant Cavity Oscillator.

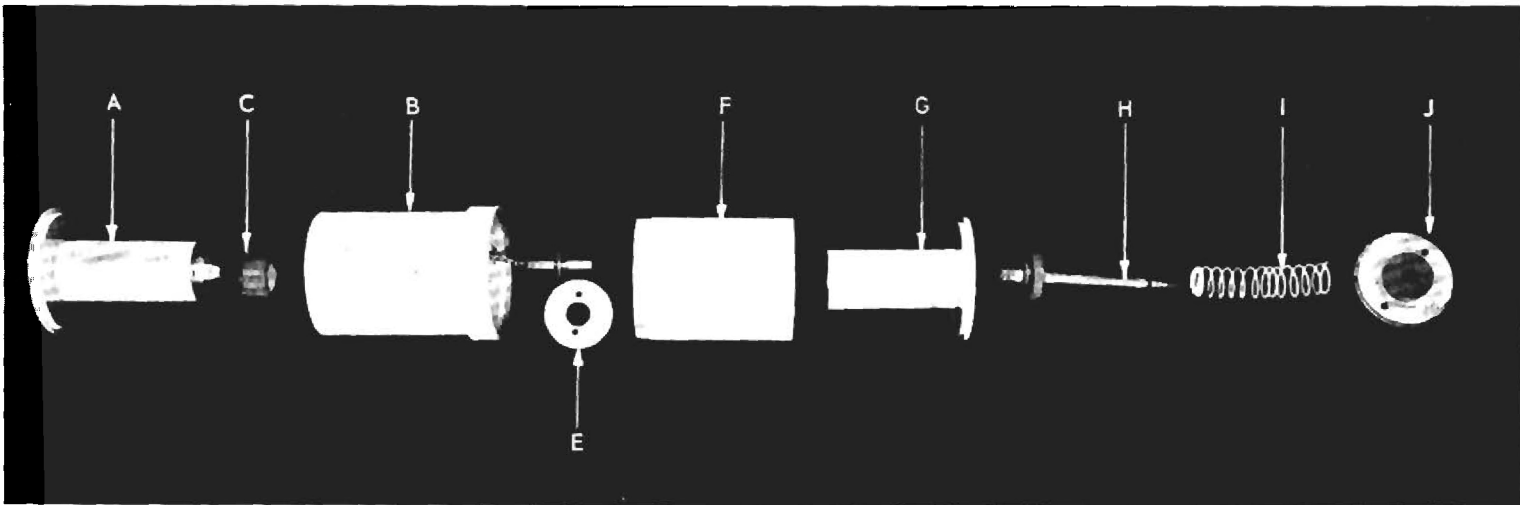


Figure 4.6. Exploded View of Re-entrant-Cavity Oscillator.

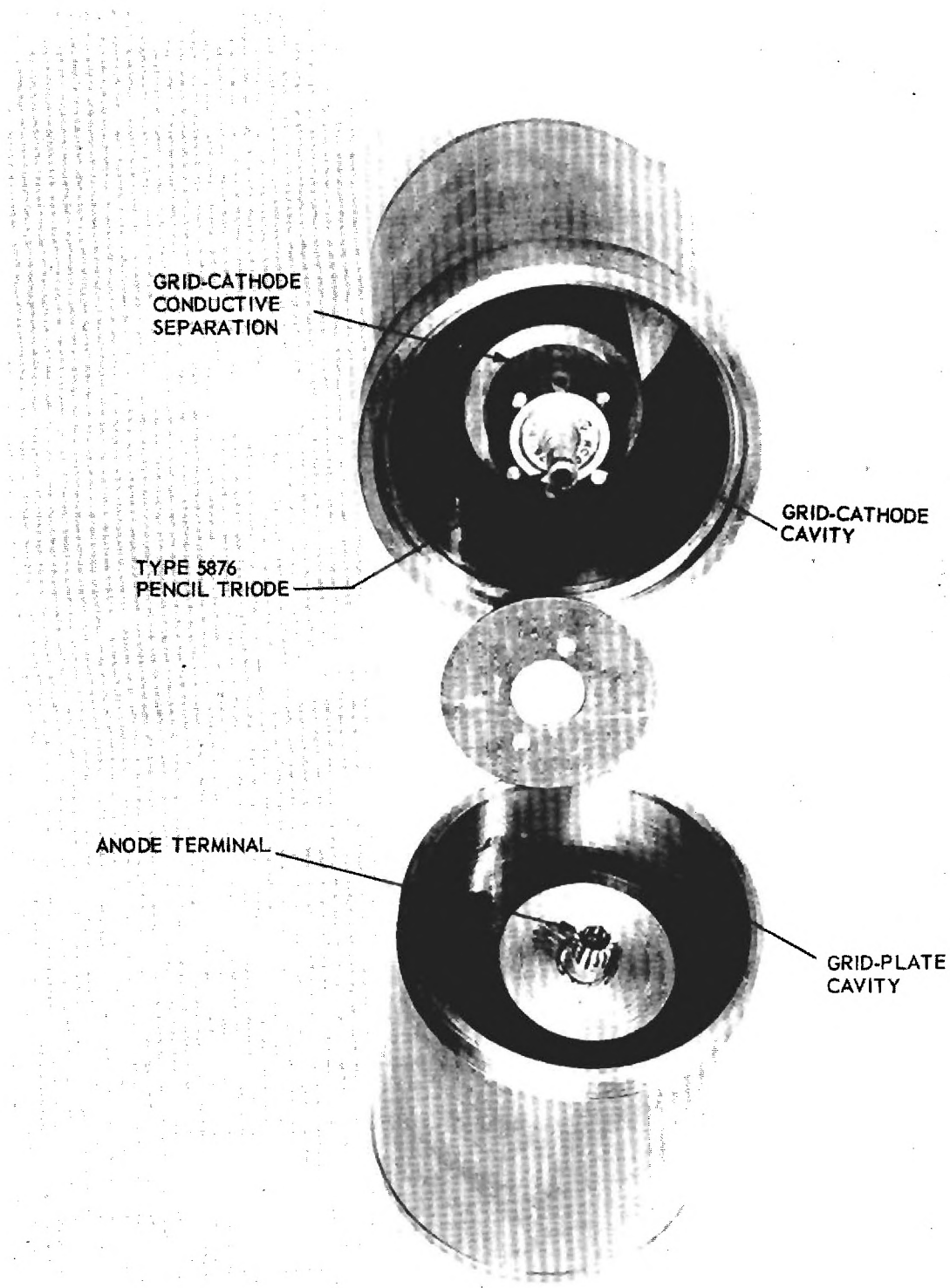
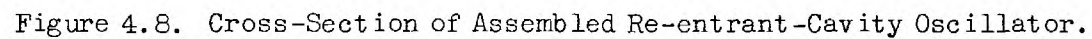


Figure 4.7. Semi-Assembled View of Re-entrant Cavity Oscillator.



to three decimal places allowing ± 0.005 - inch tolerance in normal shop practice.

The plate supply lead is brought in through the inner conductor of the plate-grid resonator and is by-passed at both ends as previously mentioned. The oscillator was tested with each of the five irises and also without an iris. Various plate voltages were used in checking the stability as a function of anode potential. The results of these tests are shown in tabular form in Table 4.1. It can be seen that the frequency is highest with no iris, and the frequency stability is best under these conditions. This corresponds to high mutual coupling between resonators and low capacitive coupling to the grid.

Another oscillator built to operate in the 800-mc region was constructed, and preliminary tests were conducted. From these early tests, orders of stability comparable to those obtained at 650 mc seem to be forthcoming. The results of these tests will be given in a later report.

The problem of tuning one of the resonators to note its effects on its stability when each of the resonators are at various resonant frequencies with respect to one another is being considered. One of the resonators will be made physically larger than the other so as to be at a lower resonant frequency. A tuning adjustment will then be inserted to tune the resonant frequency over a range so that it will actually go higher than the untuned section. Effects will be noted. These resonator sections should have the same resonant frequency when the tube is inserted.

TABLE 4.1

RE-ENTRANT TYPE CAVITY STABILITY VARIATIONS
WITH IRIS SIZES AND PLATE VOLTAGE

<u>Iris Size</u>	<u>Plate Volts</u>	<u>Plate Current</u> (ma)	<u>Frequency</u> (mc)	<u>Stability</u> (ppm/volts)
None	200	13	650	3
None	250	16	650	1.5
None	300	20	650	1.5
1 (smallest)	200	12	647	3
1	225	14	647	2
1	250	16	647	2
2	200	12	643	4
2	225	14	643	3
2	250	17	643	2
2	300	22	643	2
3	200	12	638	4
3	225	14	638	2.5
3	250	17	638	2.5
3	300	23	638	2.5
4	200	13	624	5.5
4	225	17	624	3.5
4	250	20	624	3
4	275	23	624	3
5 (largest)	150	8	612	10
5	200	14	612	3.7
5	225	17	612	3.1
5	250	20	612	2.6

V. SYNCHRONIZATION OF OSCILLATORS

If a reference signal of suitable amplitude and frequency is injected into an appropriate section of a free-running oscillator, the frequency of the oscillator may be pulled to that of the reference source. Under certain conditions the phase of the oscillator voltage may become synchronized to that of the reference so that their relative phase remains constant. In this case the oscillator is locked to the reference source and a true synchronization or locking phenomenon is said to exist. In other cases such a locked condition is not attained, but the average frequency of the oscillator is very nearly that of the reference source. In the latter case considerable frequency modulation is found to be present in the output signal of the partially synchronized oscillator. An oscillator, when operating in such a semi-synchronized or "pulled" condition, may be expected to be quite unsatisfactory as a signal source, at least from a practical standpoint because of the unwanted frequencies present.

Synchronization is of importance in many commercial applications. It is usefully employed in f-m receivers and limiters, in television, aid-to-navigation, etc. In the field of frequency control it assumes importance because of one fundamental characteristic, this being that the synchronized oscillator assumes the stability of its synchronizing source. The significance of this statement is illustrated by the effect of synchronization upon a LC oscillator of inherently poor frequency stability when the synchronizing source is the output of a highly stable, crystal-controlled oscillator. Improvements in stability of several orders of magnitude may be effected in such a case.

The capabilities of an oscillator of being synchronized are best specified in terms of a band of frequencies which extend either side of the free-running frequency. This band is termed the "band of synchronization" and is a quantity which is directly proportional to the strength of the synchronizing voltage and inversely proportional to the Q of the tank circuit in a LC oscillator. It is logical that an oscillator with a wide band of synchronization should be a convenient vehicle for the locking phenomenon and conversely for that with a narrow band. It is evident, for

example, that in the case of a wide band, the synchronizing source may vary considerably in frequency without falling outside the band and, hence, without causing loss of synchronization.

An interesting condition arises when two synchronizing signals are present. If both these signals fall within the band of synchronization, no true locking can occur. If one falls within and one without the band, their combined effect is observed in what has been designated as "combination oscillations". This effect may be interpreted as follows: the signal within the band synchronizes the oscillator to its frequency, the signal outside the band finds the oscillator serving as a regenerative amplifier and is thus amplified. In usual practice, the phenomenon is observed in the form of amplitude-modulated synchronized oscillations, the "amplitude modulation" actually being a beat phenomenon between the two signals present. Fortunately the amplitude of this beat frequency is normally very small and is usually not objectionable unless the frequency of the beat falls within the audio range.

The conditions of the preceding paragraph are particularly well illustrated by a synchronizing signal which consists of a periodically interrupted wave-train. Inasmuch as a signal of this type may be represented, through Fourier analysis, as the sum of a carrier and its sidebands, it is evident that the synchronizing action of such a signal must be considered in the light of the phenomena described in the paragraph above. If the first pair of sidebands are close to the carrier, that is, if the interrupting frequency is low, it is evident that more than one synchronizing frequency will fall within the band of synchronization and their mutual interference will result in failure of a "lock" to be observed. If, on the other hand, the first pair of sidebands are remote from the carrier, it is seen that the carrier may fall within the locking band and thereby provide true synchronization. The sidebands, falling outside the same band, produce beats phenomena in the manner previously mentioned but the "amplitude-modulation" resulting may be made negligibly small. Of particular interest is the fact that any sideband can itself act as a synchronizing source. This means that an interrupted wave-train may serve to synchronize an oscillator, separately, at each of several discrete frequencies.

A. Bandwidths and Synchronization by C-W Signals

In an important paper Adler (4) has developed a relatively simple theory by which to determine the bandwidth of synchronization in any specific LC oscillator. His analysis relates anode voltage, grid voltage and externally injected voltage in a synchronized oscillator and may be most easily understood by reference to Figure 5.1. The quantities symbolized by vectors are defined

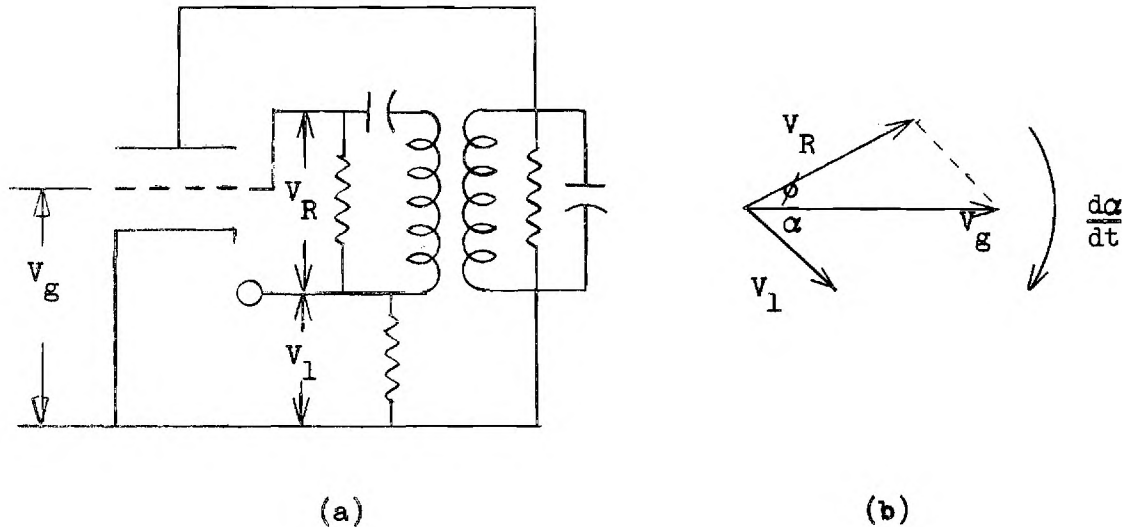


Figure 5.1. Relationships in a Synchronized Oscillator.

V_1 = externally injected signal of frequency ω_1

V_R = voltage returned from tuned circuit

V_g = voltage at grid of tube of frequency ω

The conditions defining the bandwidth of synchronization are obtained by considering Figure 5.1 b as a closed triangle. The triangle is closed when $d\alpha/dt = 0$, which is to say that $\omega = \omega_1$, or that synchronization exists.

It is evident that the grid voltage V_g is the vector sum of V_1 and V_R , and further that the phase ϕ must be due to the tuned circuit. It is known

that in a simple tuned-circuit, for small deviation of frequency

$$\phi \doteq \frac{2Q}{\omega_0} (\omega - \omega_0) \quad (5.1)$$

where ω_0 is the angular frequency of circuit resonance.

It is also evident from Figure 5.1 b that, for small ϕ

$$\phi \doteq \tan^{-1} \frac{V_1 \sin \alpha}{V_g} \doteq \frac{V_1 \sin \alpha}{V_g} \quad (5.2)$$

Equating equations 5.1 and 5.2, one obtains the important relationship

$$\omega - \omega_0 = \frac{\omega_0}{2Q} \frac{V_1}{V_g} \sin \alpha \quad (5.3)$$

from which the one half bandwidth is obtained by observing that the maximum value of α may be expected to attain, and still have synchronization maintained, is 90° . For this value of α the one half bandwidth is given by

$$\omega_c - \omega_0 = \frac{\omega_0}{2Q} \frac{V_1}{V_g} \quad (5.4)$$

where ω_c is the angular frequency at the edge of the band.

It is evident from equation 5.4 that the bandwidth is directly proportional to the amplitude of injected voltage but is inversely proportional to both the amplitude of grid voltage and to the Q of the tank circuit. If the oscillator is to be easily synchronized, it is necessary that the Q be low and that the grid drive be small. These are the usual characteristics of an oscillator of poor stability. So it may be correctly concluded that unstable oscillators are in most cases, relatively easy to synchronize while stable oscillators are difficult to synchronize.

The synchronizing process may be usefully employed in frequency multiplication; the process sometimes being described as a "pulling into phase" of every second or third cycle of the synchronized oscillator by the injected voltage and sometimes as the direct effect of the second or third harmonic of the input. In any case the magnitude of input voltage required

for synchronization is much greater for doubling or tripling than for synchronizing at the fundamental frequency.

The order of magnitude of synchronizing voltage required in UHF oscillators is illustrated by a series of tests conducted recently on this activity. The arrangement is illustrated in Figure 5.2.

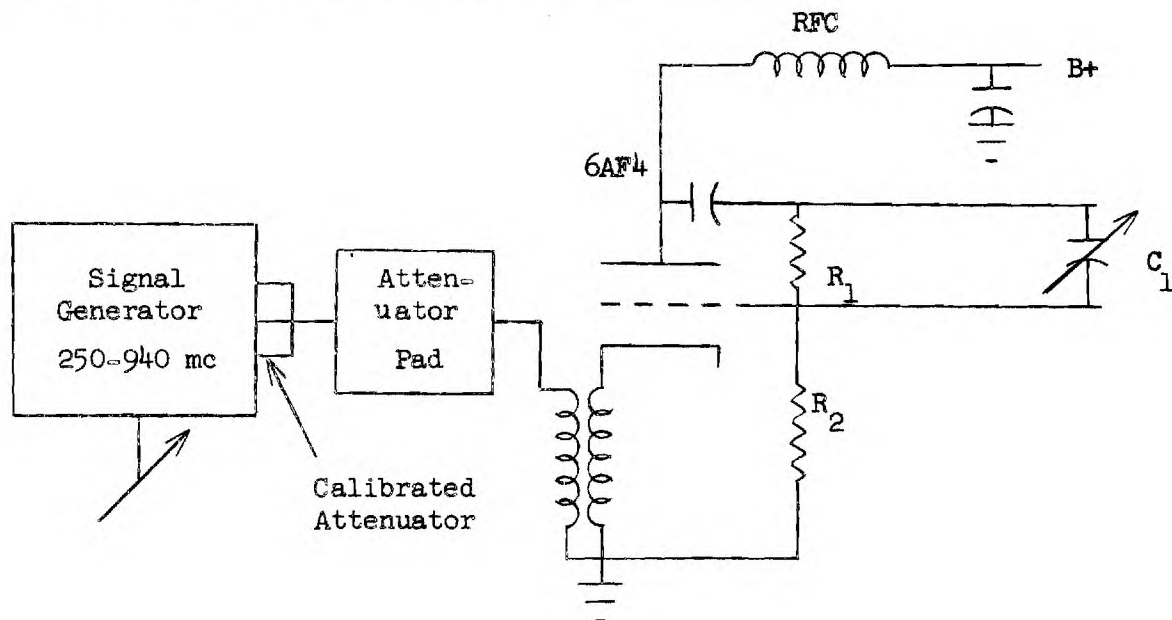


Figure 5.2 Circuit Arrangement for Synchronization Tests.

The oscillator utilizes a hairpin loop and is tuned by the small variable capacitor C_1 which terminates the loop. By selection of each several loops, the oscillator was operated at various frequencies within the region of 300 to 850 megacycles. The resistor R_1 , shown shunting the plate-to-grid load, was introduced for the purpose of deliberately degrading the Q of the oscillator tank, thereby increasing the bandwidth of synchronization and improving the tendency toward establishing a "lock" with the injected signal.

No difficulty was experienced in synchronizing the oscillator with a small signal from the generator when the frequency ratio was 1:1. Synchronization was possible, but less easily accomplished when the frequency ratio was 1:2 (i.e., doubling) and still less easily accomplished when the ratio was 1:3. The results are best described in tabular form, Table 5.1

shows the results of tests conducted in the frequency range under discussion. The following definitions apply:

f_o = free-running frequency of oscillator,

V_1 = amplitude of injected voltage,

f_1 = center frequency of injected voltage, and

$2f_c$ = width of band over which synchronization occurred.

TABLE 5.1

BANDS OF SYNCHRONIZATION

(a)		(b)		(c)		(d)	
$f_o = 336 \text{ mc}$		$f_o = 795$		$f_o = 795$		$f_o = 795$	
$f_1 = 336 \text{ mc}$		$f_1 = 795$		$f_1 = 397.5$		$f_1 = 265$	
V_1 (mv)	$2f_c$ (kc)	V_1 (mv)	$2f_c$ (mc)	V_1 (mv)	$2f_c$ (mc)	V_1 (mv)	$2f_c$ (mc)
50	64	200	1.10	500	2.0	500	0.2
100	144	300	1.5	1000	3.5	1500	1.10
200	352	500	5.5	1500	5.0	2000	1.2
500	832						

It may be seen that synchronization over that section of the UHF band under test, 300 to 800 megacycles, can be achieved by direct synchronization or by doubling (or tripling) through the synchronization process. The immediate significance is illustrated in the next section of this report, where there is described an oscillator system presently under design which aspires utilizing a tripling synchronization process as one link in its closed loop.

B. Synchronization with Interrupted Wave-Trains

Thus far the assumption has been implied, if not explicitly expressed, that the synchronizing signal is a continuous function of time and of amplitude that is essentially constant. On the basis of conjecture, it would not seem improbable that synchronization, or near-synchronization, could still exist in an oscillator if a few cycles of the injected voltage were lost because of some form of interruption. One would anticipate that during the "off" time of the synchronizing voltage that the oscillator, previously locked at the synchronizing frequency f_1 , would tend in a transitory manner toward its free-running frequency f_0 . However, if the interruption was of sufficiently small-time duration, the reapplied locking signal would quickly return the frequency to f_1 . If the periods of interruption were sufficiently short, the small transients would be essentially negligible, and one could still refer to the oscillator as "locked".

It can be quickly verified experimentally that such synchronization (or quasi-synchronization) can and does exist, and under far more general circumstances than the preceding paragraph would imply. If a signal source is modulated by a rectangular wave, so that the output consists of a time period during which a sinusoidal voltage of amplitude V_1 and frequency f_1 is present, and another equal time period during which no voltage is present, it may be demonstrated that such a signal will synchronize a free-running oscillator. In fact, the frequency of that oscillator becomes exactly f_1 , as may be proved by frequency counters and/or Lissajou patterns. A further surprising observation is that the "on" time of the synchronizing source can be considerably less than the "off" time and synchronization will still exist.

One method of explaining the phenomenon is to represent the interrupted wave-train by its equivalent Fourier series. Consider the representation of a periodic pulse of unit amplitude shown in Figure 5.3.

In the usual method (for example, see Cuccia 5) of the complex representation of a Fourier series, the coefficients of individual terms of the

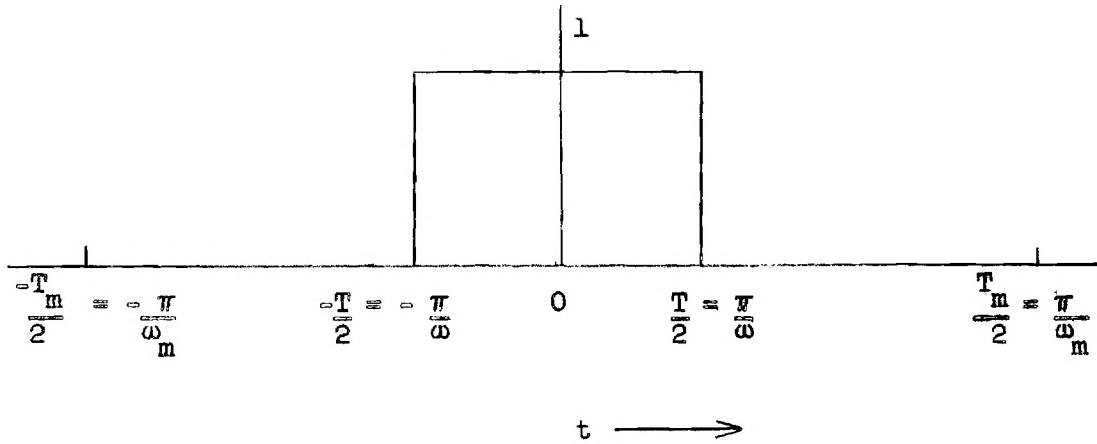


Figure 5.3. Representation of Periodic Pulse.

series are given by

$$C_n = \frac{\omega_m}{2\pi} \int_{-\pi/\omega}^{\pi/\omega} e^{-jn\omega_m t} dt, \quad (5.5)$$

whence

$$C_n = \frac{\omega_m}{-j2\pi n\omega_m} \left[e^{-j(n\omega_m \pi/\omega)} - e^{j(n\omega_m \pi/\omega)} \right] = \frac{1}{n\pi} \sin nk\pi, \quad (5.6)$$

where $k = T/T_m =$ duty cycle.

The total expression for the pulse may now be written as

$$f(t) = \frac{E}{\pi} \sum_{n=-\infty}^{\infty} \frac{\sin nk\pi}{n} e^{jn\omega_m t}. \quad (5.7)$$

Since $\sin nk\pi$ goes to zero for integral values of the quantity nk , the harmonic component whose number n is equal to $1/k$ or multiples thereof will be of zero amplitude. For example, if the pulse is a square wave, where $k = 1/2$, even-numbered components are of zero amplitude.

The spectrum of a sine wave of amplitude E and of angular frequency ω_o , which is amplitude-modulated by a rectangular pulse, can now be visualized. The wave, modulated by a rectangular wave of repetition frequency ω_m , and a portion of its spectrum are illustrated in Figure 5.4. The effect of change of duty cycle is shown.

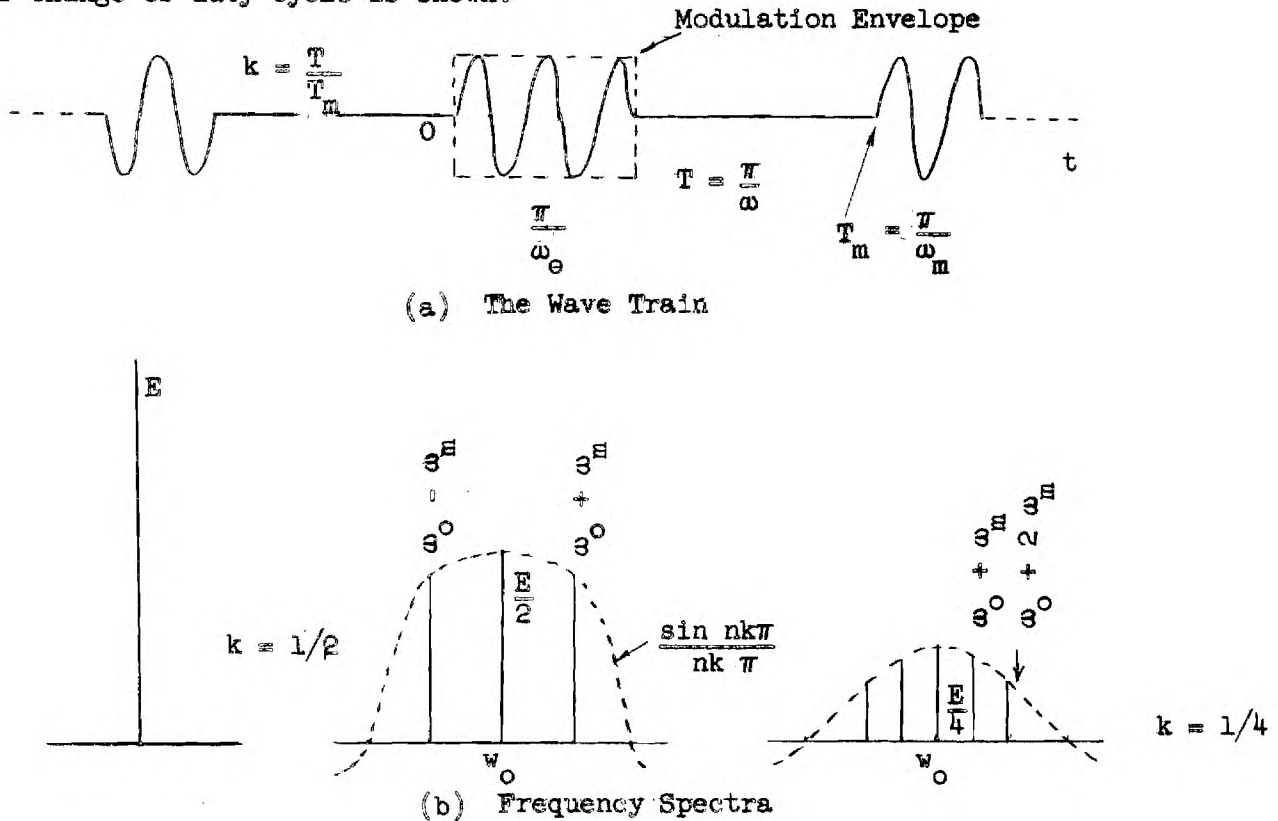


Figure 5.4. Spectra of Pulse-Amplitude-Modulated Wave as Function of Duty Cycle.

The information given by equations 5.5, through 5.7, portrayed in Figure 5.4, permits determination of the necessary relationships of amplitude, duty cycle and modulating frequency if an interrupted wave is to serve as a synchronizing source. First, it is evident that if any individual frequency of a spectrum of Figure 5.4 b is to serve as a synchronizing agent, it is evident that no other frequency of the spectrum should simultaneously fall within the band of synchronization. In that case two individual synchronizing signals would fall within the locking band. This undesirable situation can be avoided by insuring that the separation between any two

adjacent lines of the spectrum is greater than the band of synchronization, $2 \omega_c$. This is assured if

$$\omega_m > 2 \omega_c. \quad (5.8)$$

A practical aspect considered to be of considerable importance is the fact that several potential synchronizing signals are available from one original c-w signal. If the duty cycle is small, there exist several sidebands ($\omega_0 \pm n\omega_m$) of amplitude not significantly less amplitude than that of the carrier.

An experiment recently conducted on this project will serve to illustrate the phenomenon. The equipment arrangement is shown in Figure 5.5.

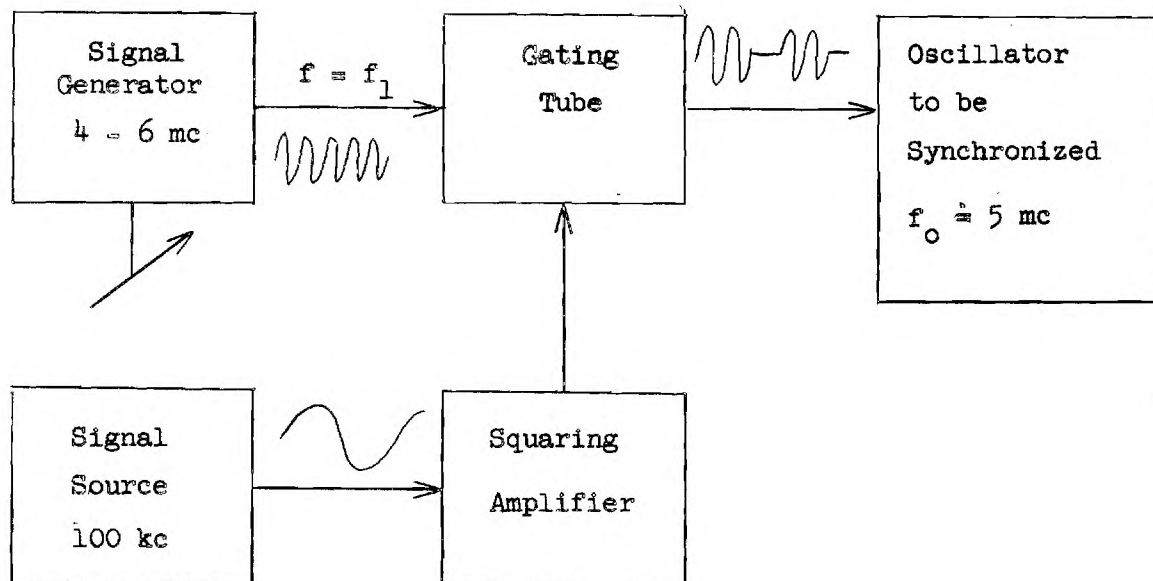


Figure 5.5. Equipment Arrangement for Synchronization by Interrupted Wave-Trains.

The free-running oscillator was operated at a nominal frequency of five megacycles. The amplitude of input signal was first adjusted so that the band of synchronization was about 50 kilocycles, thus satisfying the requirements of equation 5.8. The frequency of the signal generator was then varied

over the band of synchronization. The synchronized oscillator followed smoothly, exhibiting the same stability as that of the signal generator. The envelope of oscillations showed a small amount of 100-kilocycle amplitude modulation.

The synchronizing action can best be demonstrated by tuning the tank circuit of the free-running oscillator in amounts sufficient to cover the entire frequency spectrum illustrated symbolically in Figure 5.4 b. If proper action occurs, the oscillator should change frequency in a series of "jumps" rather than continuously as its center frequency falls successively inside the "band of synchronization" associated with each of the significant sidebands. In the test illustrated in Figure 5.5, the signal generator, rather than the oscillator, was varied in frequency. The action that occurred is best illustrated by reference to Figure 5.6, in which f represents the frequency of the "oscillator to be synchronized" and f_1 represents the frequency of the signal generator.

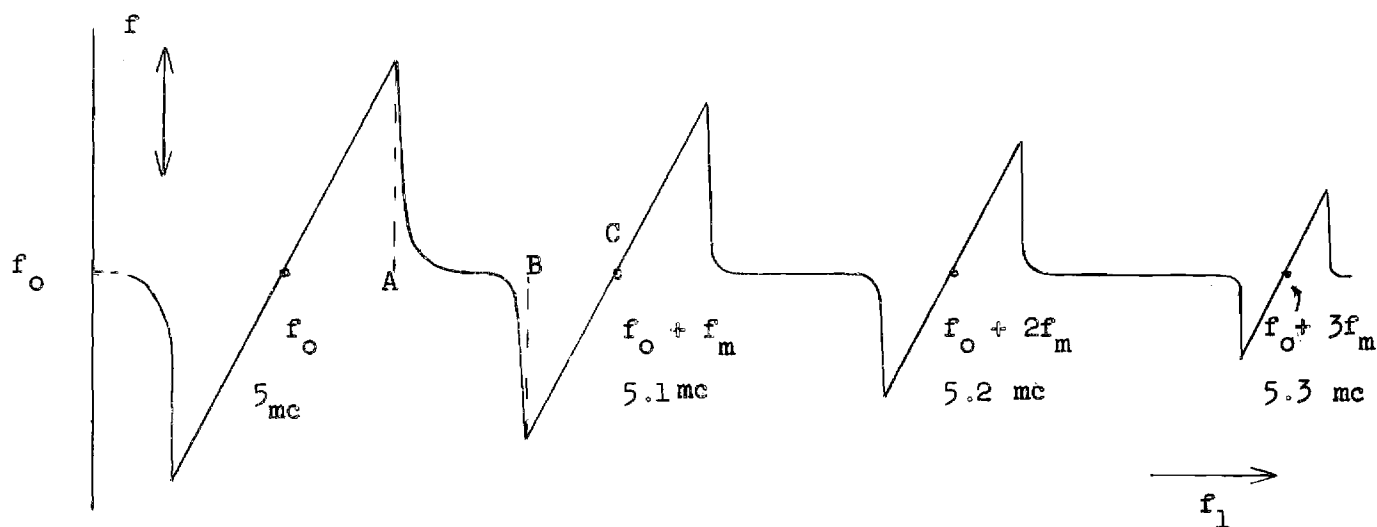


Figure 5.6. Synchronizing Action of Interrupted Wave-Train.

The figure illustrates the synchronizing action of the carrier and its upper sidebands. The action for the lower sidebands and carrier is a mirror image of that shown. The action is explained as follows: when the signal generator frequency f_1 is moved back and forth through f_0 , the actual frequency of the oscillator follows in a one-to-one relationship, resulting in a straight plot. As the frequency f_1 is increased to the point marked A synchronization is lost and the oscillator returns to its frequency f_0 . However, if f_1 is further increased, there is a point B at which synchronization is abruptly gained once more. At point C synchronization exists, the signal generator injecting a signal of 5.1 megacycles, the oscillator running at 5.1 megacycles minus 100 kilocycles (f_m) that is, at 5.0 megacycles. The same action is illustrated as f_1 is further increased, bands of synchronization being evident centered at the frequencies $f_0 + 2f_m$ and $f_0 + 3f_m$. It is of interest to note that, in theory, the amplitude of input at the frequency $f_0 + 2f_m$ should be zero, since the modulating signal is a square-wave (i.e., $k = 1/2$). In practice enough non-symmetry exists to result in some output at the frequency of the second sidebands.

A total of seven synchronized regions exist, if the three lower sidebands are added to those shown. If the duty cycle were less, more sidebands of significance appear and a greater number of frequencies can theoretically be synchronized. The method illustrated is believed to show promise in producing an oscillator which will tune to any of a large number of discrete frequencies when the controlling source consists of one stable h-f oscillator and one stable l-f (interrupting) oscillator.

VI. REACTANCE-TUBE OSCILLATOR

In previous Progress Reports (1,2) methods have been described for constructing discriminators having steep slope characteristics for use in the UHF band. Unfortunately, it was pointed out that there was really no known useful way that these steep slope characteristics could be used in controlling the frequency of UHF oscillators, unless these UHF oscillators happened to be klystrons. However, from a different viewpoint, a triode oscillator might be controlled with such a discriminator output through a complex servo and motor combination and good long-term stability might be thereby obtained.

In the preceding section V, methods of synchronizing oscillators on the second and third harmonics of the synchronizing source were described, and this development led to the hope that the UHF discriminator could be used to actually control the frequency of the lower-frequency synchronizing source.

As a preliminary test, a reactance-tube oscillator was constructed to operate in the 200-mc range with the thought in mind that this signal source could be used to synchronize an oscillator in the 600-mc region through a tripling process. The output of the 600-mc oscillator could then be applied to the UHF cavity-discriminator circuit whose output could be used to control the 200-mc reactance-tube oscillator.

The reactance-tube oscillator was constructed utilizing the circuit and principles described in reference 6. A schematic diagram of this circuit is shown in Figure 6.1.

The principle of operation is self-evident from the schematic diagram. The oscillator tube is on the left. Its grid and plate are connected between the two ends of the terminated half-wave length cable which is of 100 ohms characteristic impedance in this experimental model. The cable was actually terminated in 200 ohms, because the oscillator failed to operate with 100 ohms.

The plate of the reactance tube is connected to the plate of the oscillator, and the grid is moved along a tap connection on the line. In this way one obtains a point corresponding to a position which is a quarter

wavelength from the plate end of the line. Under these conditions the reactance tube is driven by a signal which is 90 degrees lagging that of the plate. Thus, the reactance tube appears as an inductance shunted across the oscillator, since it draws quadrature current.

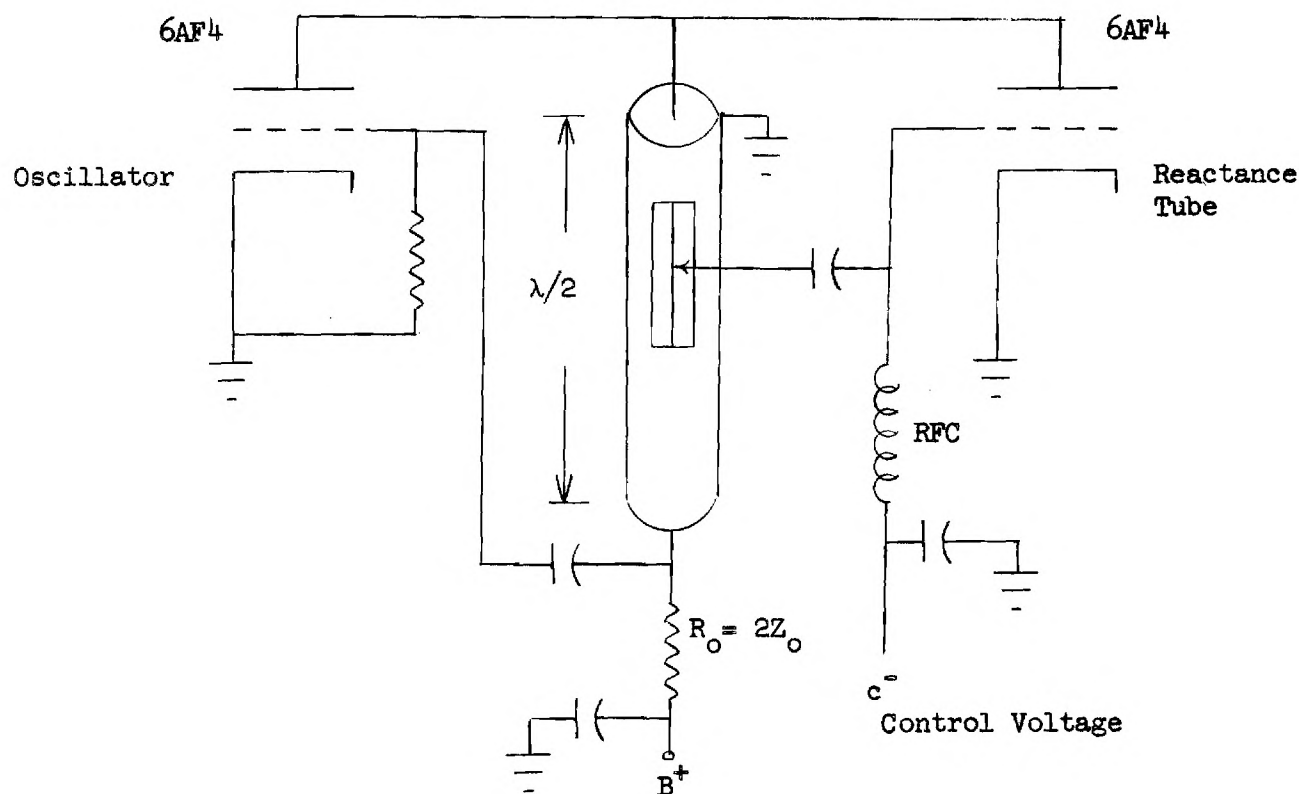


Figure 6.1. Reactance-Tube Oscillator Schematic.

If the transconductance of the reactance tube is varied, the amount of quadrature current and thus the inductance is varied. This is conveniently done by varying the grid bias on the reactance tube.

The completed assembly showing the half-wave length line and the associated curcuitry is shown in the accompanying photograph, Figure 6.2. The line was constructed from two pieces of quarter-inch-thick brass.

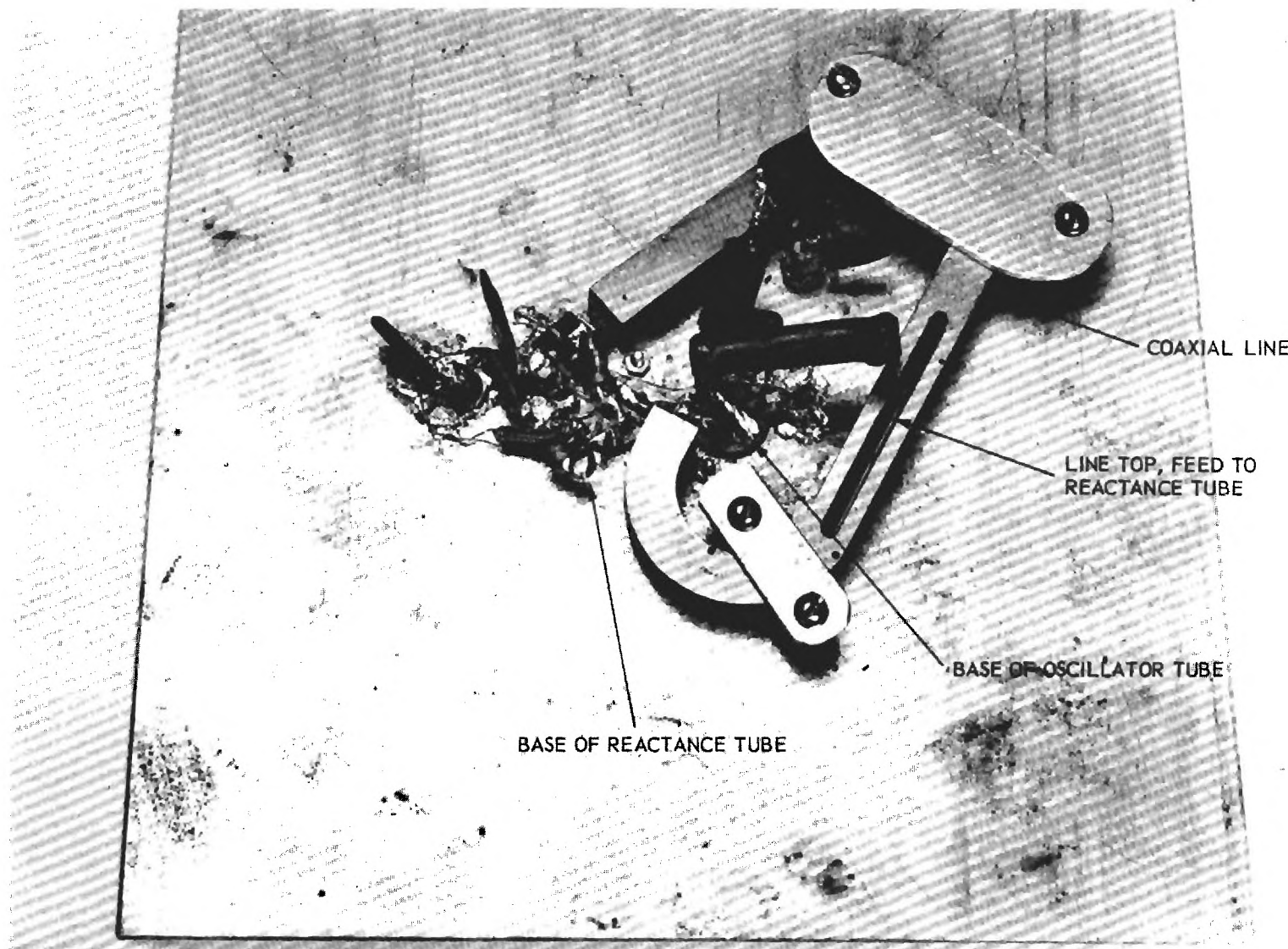


Figure 6.2. Photograph of Assembled Reactance-Tube System.

Each piece was grooved with a ball mill of 3/16-inch diameter to a depth of 3/32 inch. The construction is seen from Figure 6.3, in which the pieces are shown disassembled. The inner conductor was made by stripping the outer conductor from a length of 93-ohm RG 62/U cable. The insulation was taken off the inner conductor in the region of the slotted portion to provide a grid-connecting point.

Tests were run by varying the bias on the reactance tube from minus 1.6 to minus 15 volts. Table 6.1 shows the results.

TABLE 6.1

REACTANCE TUBE FREQUENCY VARIATIONS

<u>React Grid</u>	<u>Plate Volts</u>	<u>Total Current</u> (ma)	<u>Output</u>	<u>Frequency</u> (mc)
15	100	27	3.7	188.36
10	100	28	3.8	188.64
9	100	28	3.8	188.70
8	100	29	3.9	189.40
7	100	30	3.9	189.98
6	100	32	4.4	191.264
5	100	35	4.8	192.86
4	100	38	5.3	194.90
3	100	40	5.7	197.10
2	100	42	6.0	199.40
1.6	100	43	6.0	201.58

Except for the disturbingly low output voltage, the results were reasonably satisfactory. A change of approximately five per cent in frequency due to d-c applied to the reactance tube should give reasonable control of the system. Although it has not as yet been attempted, this arrangement may provide control at frequencies as high as 400 mc. If so, by a tripling process the system could be used to control an oscillator in the 1200-mc region.



Figure 6.3. View of Disassembled Line.

The complete automatic frequency control loop is shown below in a block diagram in Figure 6.4. This configuration has not been completely constructed at the writing of this report, but should be finished and tested shortly. The data will be given in a subsequent report.

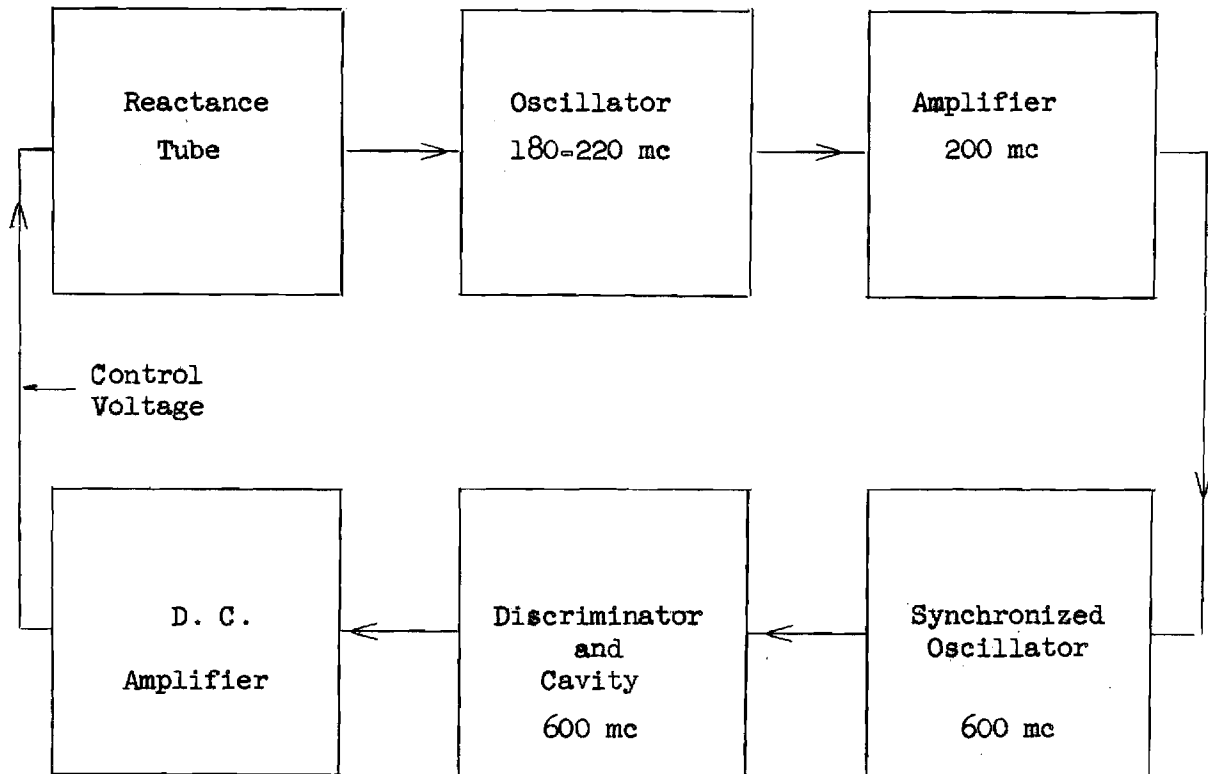


Figure 6.4. Complete AFC Loop for 600-Megacycle Oscillator.

VII. CONCLUSIONS

Cavity-controlled oscillators employing the electron-tube interior to the cavity and using small series capacitors to steepen the reactance-versus-frequency characteristics of the cavity provide attractive form factors in the 400-to 700-megacycle range and also exhibit encouraging orders of frequency stability. A nickel-steel of low expansivity, Invar, can be employed to form the cavity proper and to reduce drastically the temperature sensitivity of the associated oscillators.

Pencil triodes do not operate satisfactorily in a simple series-reactance cavity-controlled oscillator but can be very satisfactorily employed in the re-entrant type of cavity. The configuration involved employs two shorted quarter-wave coaxial cavities joined end-on by the triode. A circular iris lying in the grid-plane controls the magnitude of both plate-grid coupling and plate-cathode feedback. This type of oscillator appears capable of stable frequency control at frequencies in excess of 1000 megacycles.

The synchronization of an oscillator by a small injected signal from a stable source is a convenient method of frequency stabilization in the lower UHF region. Oscillators using conventional UHF triodes and operating in the 600-900 megacycle range can be synchronized by the fundamental, second harmonic, or third harmonic of an injected signal. In addition, synchronization can be effected by both fundamental and primary sidebands of an interrupted wave-train.

Automatic frequency control in the UHF region may be provided by a reactance-tube oscillator combination which employs a half-wave coaxial line as a tank circuit. A center tap in the coaxial line provides the desired phase difference in the input to the reactance tube. A frequency swing of 20 megacycles has been recorded at a nominal center frequency of 200 megacycles in a combination of this kind. By a system of doubling or tripling, control can be extended into the UHF region.

VIII. PROGRAM FOR THE NEXT QUARTER

Primary attention will continue to be devoted to oscillators and to determination of the long-term stability of those constructed. Efforts will be directed toward establishing satisfactory frequency standards as adequate tools for precise determination of frequency variations of UHF oscillators.

The investigation of re-entrant type cavities employing pencil triodes will be continued, and the upper frequency limit of the configuration will be the subject of special attention. Invar cavities, successfully employed in simpler arrangements, will be tested in the re-entrant type.

Frequency control by synchronization of interrupted wave-trains will be further investigated. If adequate means of providing the interrupted wave-train are assured, efforts will be directed toward construction of an oscillator system which can be synchronized at any of several discrete frequencies by such an input.

Frequency control by discriminator action will be given some attention. In particular, efforts will be made to extend the frequency range of simple reactance-tube oscillator combinations into the UHF region.

Respectfully submitted,

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by *E. G. H.*
Donald W. Fraser
Project Director

Edward G. Holmes
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Approved:

J. E. Boyd
J. E. Boyd, Head
Physics Division

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Paul K. Calaway, Acting Director
Engineering Experiment Station

IX. IDENTIFICATION OF KEY TECHNICIANS

This project is under the direction of Mr. Donald W. Fraser who devotes one-third time to this work at present. He is Assistant Professor of Electrical Engineering at Georgia Tech and holds the degree of Master of Science in Electrical Engineering from this institution. He worked on station project 131-45, "High Frequency Crystal Controlled Oscillators," devoting approximately one-fourth time to it. His other experience includes five years of electronic testing and research in the U. S. Navy.

Mr. James C. Sellers joined the project as Electronics Technician at its onset. He is concurrently devoting full time to the project. Mr. Sellers previously was engaged for eight years in nuclear instrumentation with the AEC at Oak Ridge, Tennessee, where he had extensive experience as a technician in the design, assembly and testing of electronic circuits.

Mr. James C. Hogg, Jr., Assistant Research Professor, devotes approximately one-third time to the project. Mr. Hogg holds the degree of Master of Science in Electrical Engineering from the Georgia Institute of Technology. Mr. Hogg has had extensive experience in circuit design and oscillators, both in the industrial and the research field. He was employed on a full-time basis on the S.C.E.L. projects, "High Frequency Crystal Controlled Oscillator Circuits" and "Investigation of Frequency Control Above 150 mc."

Mr. Edward G. Holmes has recently joined the project. Mr. Holmes holds the degree of Master of Science in Electrical Engineering. His experience in the electronics field includes five years of work with frequency-measuring apparatus and broadcasting equipment, two years as Electronics Officer in the U. S. Navy and three years of research and development work in UHF and microwave equipment. He is now devoting approximately three-fourths time to the project.

Progress Report No. 6, Project No. 229-198

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ENGINEERING EXPERIMENT STATION
of the Georgia Institute of Technology
Atlanta, Georgia

PROGRESS REPORT NO. 7

PROJECT NO. 229-198

PRECISION FREQUENCY CONTROL TECHNIQUES
(500 Mc and Higher)

By

DONALD W. FRASER AND EDWARD G. HOLMES

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CONTRACT NO. DA-36-039-sc-42590

DEPARTMENT OF THE ARMY PROJECT: 3-99-11-022
SIGNAL CORPS PROJECT: 33-142B

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AUGUST 1, 1954 to NOVEMBER 1, 1954

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FORT MONMOUTH, NEW JERSEY

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I. PURPOSE

The purpose of this project is threefold: (a) to continue work on stabilization of oscillators between 500 and 3,000 mc, using cavity resonators, (b) to continue to work on frequency control utilizing high-order overtones of quartz-crystal blanks and (c) to undertake any other investigations which may arise during the course of the work outlined in (a) and (b) above, or which may be mutually agreed upon between the Contractor and the Contracting Officer or his representative.

By agreement with the sponsor, investigations of resonances below 500 mc may be prosecuted as preliminary steps in determining the feasibility of frequency control by the phenomena under study. In addition, cavity resonators previously under construction and designed to provide control of frequencies below 500 mc may be completed and tested as aids in perfecting measurement techniques which will later be applied to the range of frequencies above 500 mc.

II. ABSTRACT

A primary objective during the period of this report has been the accurate determination of the frequency stability of several cavity-controlled oscillators which operate in the 500-800-mc region. A secondary objective has been the determination of the heat-transfer characteristics of coaxial cavities constructed in entirety of the nickel-steel alloy, Invar. A third, and minor, objective has been a re-examination of the possible utilization of ceramic materials in electrical resonators.

Accurate determination of frequency stability has been made possible by the assembly of highly stable frequency standards, amplifiers and mixers. Data accumulated to date indicate that the errors in measurement do not exceed 1 part in 10^7 and usually are not worse than 3 parts in 10^8 . This can be reduced, if necessary, to one part in 10^8 .

Actual frequency measurements have been restricted to three oscillators, a brass, 600-mc, cavity-controlled oscillator, an Invar, 600-mc, cavity-controlled oscillator and an 800-mc, re-entrant type, cavity-controlled oscillator. The measurements were preceded by investigations of the heat-transfer characteristics of the Invar cavity. It was revealed in these tests that abrupt changes in ambient temperature produce anomalous effects on frequency due to the extremely slow transfer of heat throughout the cavity. The recorded heat-transfer characteristics have been utilized in analyzing frequency-deviation curves of the Invar oscillator. All three oscillators, when subjected to very slow changes of ambient temperature, have exhibited changes in frequency which would be predicted from the coefficients of expansion of the inner conductor of the coaxial cavity. The coefficient, in the case of the Invar cavity, is very nearly one part per million per degree centigrade.

Investigations of ceramic bases in electrical resonators have been pursued, and new methods of attaching conductive coatings have been tested. One of these methods is designed to coat the ceramic with a smooth, firmly adherent glaze which in turn serves as a base for the conductive coatings. The other method employs an ion bombardment and sputtering technique which places a metal coating directly upon the ceramic. Both of these methods show some promise and are planned to be the basis of further investigations.

III. CONFERENCES

Members of this project, Mr. Fraser and Mr. Hogg, visited Squier Signal Laboratories during the period of 16-18 August, inclusive. During the conference the activities previously or presently engaged in by this project were reviewed. Thereafter plans for activities during the remainder of the project were formulated. It was decided that the principal objective should be to tabulate more definitively the characteristics of the previously constructed cavities and cavity-controlled oscillators. In order to complete this tabulation, frequency-measuring and temperature-measuring equipment of greater accuracy than presently available would be required. Hence it was further decided that emphasis should be directed toward construction or acquisition of equipment of greater precision. In addition, there was to be a renewal of investigations of the possibilities of using ceramic materials in electrical resonators.

IV. FREQUENCY MEASUREMENTS ABOVE 500 MC

The design and construction of precision frequency control devices requires the availability of testing equipment with which to determine the stability of final assemblies. In the early days of the present contract no equipment was available by which either frequency or frequency drift could be determined accurately in the UHF region. However, the situation was considerably improved by the acquisition of a Gertsch FM-3 frequency meter. This meter has an accuracy of one part in 10^5 and has a short-term stability, defined in terms of drift around the center frequency, which has been demonstrated to be at least one order of magnitude better. Hence, this meter has been invaluable in determining such items as effect of plate and filament voltages on the frequency of an oscillator under test and in measuring the frequency drift of resonant cavities under the influence of varying ambient temperatures.

The recent completion of oscillators with nominal frequencies of 600 mc, 800 mc and 1000 mc, which have shown promise of improved stability, has resulted in a need for frequency-measuring equipment having relatively high orders of accuracy. In order to satisfy this need efforts have been directed, during the period of this report, toward the assembly of a frequency-measuring system which would permit both short-term and long-term frequency measurements in the frequency range from audio frequencies upward to at least 3000 mc. The ultimate aim was to obtain an accuracy better than one part in 10^6 . A first version of such a system has been completed and is performing satisfactorily at the frequencies now being measured (620 and 800 mc). The remainder of this section of the report describes the system in some detail and comments upon its accuracy and the magnitude of signal required for proper operation.

A. Outline of the System

The system is comprised basically of a heterodyne assembly, beat-frequency amplifiers and a frequency counter. The stabilities required are established by the introduction of stable signals from each of two secondary frequency standards. One of these is a 100-kc Loran standard, and the other is a 50-mc crystal-controlled oscillator with special design features to improve stability.

The operation of the system is best illustrated by reference to the block diagram of Figure 4.1. The applicable frequencies as well as their orders of stabilities are indicated thereon. Harmonics of 50.0 mc mix with the output of the oscillator under test. The amplified difference frequency is fed to the frequency counter where further heterodyne action occurs reducing the signal to a frequency of less than 1 mc. It is then counted, and its value indicated on a decade display system.

B. Description of Units

1. The 50-Mc Secondary Standard

This unit is based upon a crystal-controlled oscillator which employs the third overtone of a 16-2/3-mc crystal in a C. I. Meter circuit. A buffer and an output amplifier complete the signal channel. A regulated power supply is contained in the same chassis and also a thermostatically-controlled oven whose purpose is to maintain constant temperature on the crystal. A Lavoie type K0000-0006 oven is utilized in this assembly.

Relative insensitivity to variations in ambient temperature is achieved by the crystal oven and by utilization of variable capacitors with low temperature sensitivity. These capacitors, which individually tune the plate and the grid quarter-wave lines, are type VC-11, manufactured by the JFD Company. They have a claimed temperature coefficient of zero.

The circuit of the signal channel is shown in Figure 4.2. The output into a 100-ohm cable is nominally 3-volts rms.

2. Harmonic Multiplier

The harmonic multiplier is a commercial unit available under the trade name of the Presto Microwave Secondary Frequency Standard, Model 100. In its original form it includes a self-contained, 50-mc, crystal-controlled oscillator. This crystal is not enclosed in an oven, hence suffers from temperature effects. For this and other reasons the internal oscillator was inactivated and utilized as an amplifier for the 50-mc signal originating in the circuit described in section A-1.

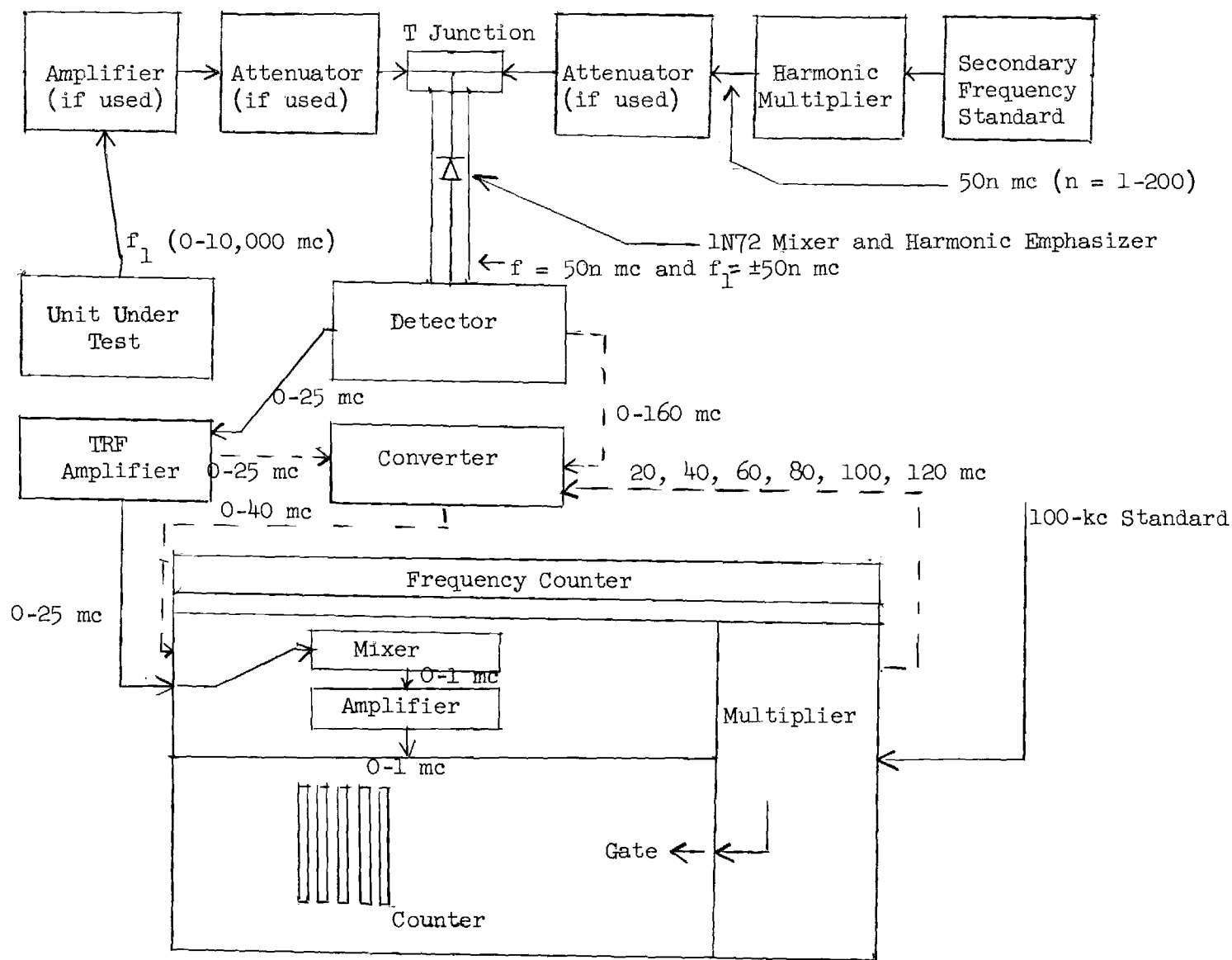


Figure 4.1. Block Diagram of Frequency-Measuring System.

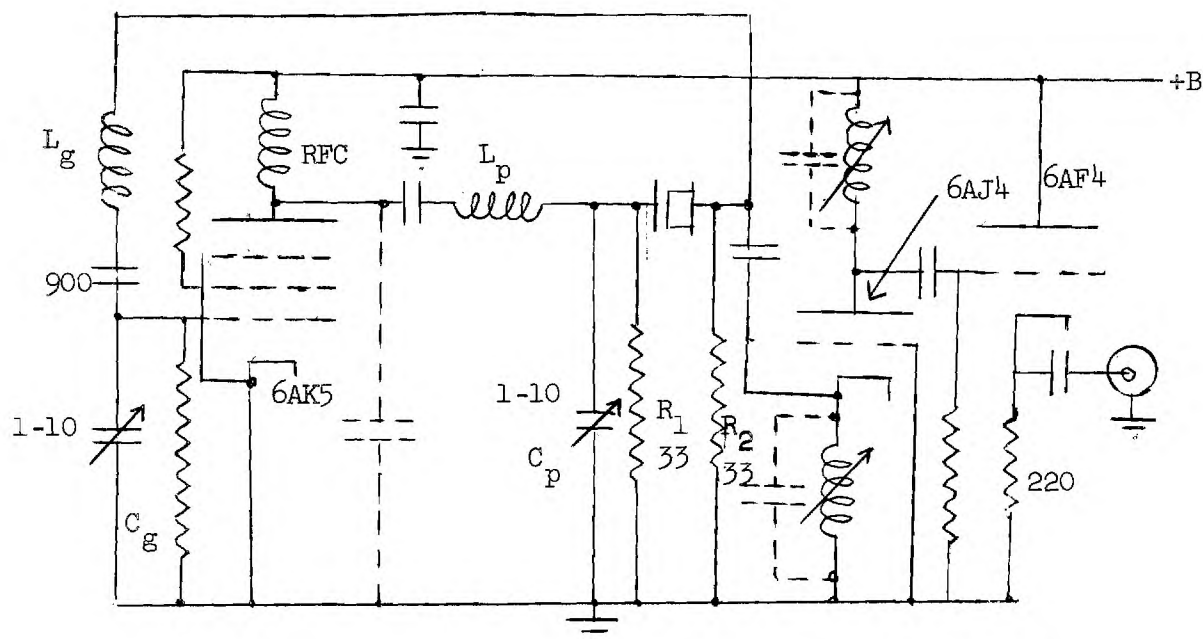


Figure 4.2. A 50-Mc Oscillator as Secondary Standard.

A block diagram of the equipment is shown in Figure 4.3. The 200-mc signal, containing also 50- and 100-mc components of considerable magnitude, is injected into a silicon-diode crystal. The combined holder and diode is of a special design stated to incorporate features which enhance microwaves. The output consists of a harmonic series of uninterrupted CW markers. The power level at any particular frequency is stated to be inversely proportional to its harmonic number. However, in the range of 600-1000 mc considerable variation in the individual strengths of the various 50-mc harmonics has been found, the multiples of 200 mc being considerably stronger than those of 100 mc and of 50 mc.

3. Mixers and Detectors

Inasmuch as the mixers and detectors may be expected to be fed from low impedance sources, at UHF and microwaves, it may be anticipated that crystals having relatively high conductivity would give a more satisfactory output than would crystals of higher impedance. This has been found to be the case in the 500-1000-mc range. A type 1N72 germanium diode has proved to be the most satisfactory of any utilized.

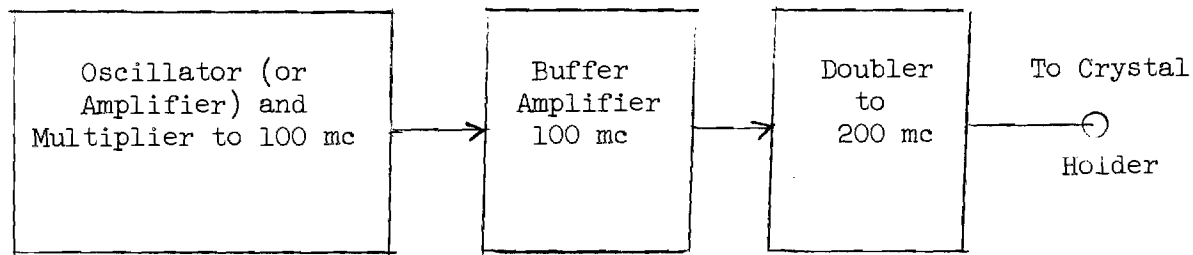


Figure 4.3. Block Diagram of Harmonic Generator.

4. The 100-Kc Secondary Standard

This signal originates in a Western Electric type D-175730 Frequency Standard, is amplified, multiplied to 1 mc and fed by a cathode follower into a coaxial cable. The standard itself remains immobile, but the amplified and multiplied signal is delivered by cable to several research areas in order to permit mobility of the complete frequency-measuring system.

This 100-kc standard is checked daily during working hours against WWV. It has consistently demonstrated an accuracy of considerably better than one part in 10^8 , hence the stability of the gate in the counter is of the same order of accuracy.

5. The Frequency Counter (and Converter)

The counter system, as presently employed, consists of two basic units. One is a Berkeley type 5575 VHF Frequency Converter, and the other is a Berkeley Type 5570 Frequency Meter. The converter is available for the purpose of reducing frequencies by heterodyne action to frequencies of less than 40 mc. The converter will accept signals of not greater than 160 mc and the frequency counter will measure frequencies of less than 41 mc.

The required accuracy is again based upon the 100-kc standard. This stable signal is multiplied to one megacycle and injected into the frequency counter where it replaces an internally-generated signal of the same nominal frequency. Further multipliers and harmonic emphasizeers produce integral multiples of one megacycle, each multiple having the same nominal accuracy as the original 100-kc signal. The frequency to be measured is heterodyned against one of these harmonics and reduced to a frequency of less than 1-mc. It is then applied to the counter system proper where it is counted during a two-second interval. The accuracy of the counting period, or gate, is controlled by the 100-kc standard by means of a dividing network.

The maximum error in determining any frequency is the sum of the maximum errors of the 50-mc secondary-standard, of the 100-kc standard, and of the counter system. The stability of the 50-mc standard is about one part in 10^7 , measured over a period of one day, and is considerably better for shorter periods of time. The 100-kc standard has a stability of not worse than one part in 10^8 . The counter system, using the accurately controlled gate, demonstrates no relative error except for an inherent plus-or-minus one count in a counting interval.

From the foregoing discussion it is seen that the accuracy of measuring frequencies above 160 megacycles is determined for the most part by the 50-mc secondary standard if readings are taken over an interval of several hours. This implies, of course, that the 50-mc standard is checked only at the beginning of the measurements. If a frequency of 620-mc is to be measured, for example, the 12th harmonic of the 50-mc oscillator is utilized in the heterodyne action. This 12th harmonic has an error of no more than 60 cycles, and hence the difference frequency is then 20×10^6 cycles plus or minus 60 cycles. The nominal 20-mc difference frequency has thus been measured within 1 part in 10^8 plus or minus 1 cycle, or a total possible error of 1.2 cycles. The 620-mc measurement is less than 62 cycles in error which is one part in 10^7 , as measured over a period of several hours.

An accuracy of 1 part in 10^7 is considered to be satisfactory for measurements being made at present. If higher orders of accuracy are needed, it will be necessary to monitor the 50-mc standard. If this is done, then an accuracy of one part in 10^8 could be anticipated.

V. RE-ENTRANT TYPE OSCILLATOR AT 800 AND 1000 MC

A description of a re-entrant type cavity oscillator was given in Progress Report No. 6 (1). The results of several tests performed on a 650-mc oscillator of this type were encouraging and have led to the construction of two additional re-entrant, brass, cavity-controlled oscillators. These operate in the 800- and 1000-mc region, respectively. In the tests on the 650-mc oscillator no power was extracted from the resonators other than the leakage from the lead-in wires to the filament and the plate. In the case of the 800-mc oscillator an attempt has been made to obtain sufficient power to drive a buffer-amplifier stage. Voltages of the order of one volt across 50 ohms are obtained.

The tube type utilized in these oscillators is a 5876 pencil triode. The pencil triode, re-entrant type, cavity-controlled oscillator appears to lend itself to control by an external cavity, as well as by internal control, because of its physical configuration which includes a plate-to-grid line and a grid-to-cathode line. If it is possible for a cavity to operate at its resonant frequency and to control simultaneously the frequency of an oscillator, one should expect results in frequency stability to be of a high order of magnitude because of the rapid change of phase at resonance. Several possible configurations which might utilize an external cavity in conjunction with the re-entrant cavity oscillator are discussed in the following paragraphs, and the results of testing one of these configurations are briefly summarized.

A. Description of Re-entrant Cavity Oscillator

No significant changes in the construction of the 800-mc oscillator were made as compared to the oscillator designed to operate in the 600- to 650-mc region. One small change was the insertion of an output loop connected to a BNC-type connector at the cathode end of the structure. Another change was previewed in Progress Report No. 6 (1) when attention was directed toward the possibility of tuning either the plate-to-grid or grid-to-cathode resonator with respect to each other by means of a tuning screw. By its action it is presumed that the optimum condition for best stability may be determined. Such a tuning screw was inserted in the 800-mc oscillator, in this case in the grid-to-cathode resonator. Results of its effect appear in the next paragraph.

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The 1000-mc, re-entrant cavity differed from the 600- and 800-mc cavities which were made with separate plate-to-grid and grid-to-cathode outer conductors. These resonators were mechanically coupled by a sleeve. The primary purpose of the mechanical sleeve had been for use as a base for inserting tuning screws, but these screws have been superseded by "irises" in later models which have the purpose of changing the grid drive and of changing frequency. In the new configuration it was expedient to discontinue the use of the sleeve and to construct the outer member of a continuous piece of brass tubing.

B. Stability Tests

Several sizes of irises, flat rings extending the grid diameter, were used in the 800-mc cavity oscillator. Different values of grid resistance were also employed. In Figure 5.1 the results of a few tests are plotted wherein iris sizes and resistor sizes appear as parameters. The instability of the oscillator is seen to be reduced when the plate voltage is increased, exactly as occurred in the earlier 600-mc oscillator. The instability is also reduced as the iris size is made smaller, and finally the combination of highest plate voltage and no iris at all resulted in the best stability of all those illustrated.

It was not possible to make the configuration oscillate when no iris was present and with the grid resistance reduced to 1200 ohms. However, grid resistors of 1700 and 2200 ohms did allow the circuit to oscillate when no iris was in place. The use of the 1700-ohm grid resistor resulted in slightly better stability than was evidenced during the use of the 2200-ohm resistor. The plate dissipation was very high in both cases, thus indicating that the grid drive, and hence grid bias, is greatly reduced and that the tube operates into a very low conductance.

The addition of the iris resulted in greater grid drive, a condition indicated by lower plate current. The lowest plate current and the lowest frequency were obtained when the largest iris was employed. The oscillating frequency for each case is indicated on its respective curve.

After conclusion of these tests, the output loop and tuning screw in the cathode-grid resonator were installed. It was found necessary to add an iris in order to obtain sufficient output to be measured with a 0-1-volt, vacuum-tube

voltmeter. The frequency of oscillation was 781.5 mc before insertion of the tuning screw, but as the screw insertion was increased the frequency was lowered to a minimum of 767.9 mc at which point oscillations completely ceased. The instability of this arrangement was nearly constant at all positions of the tuning screw until the tube stopped oscillating.

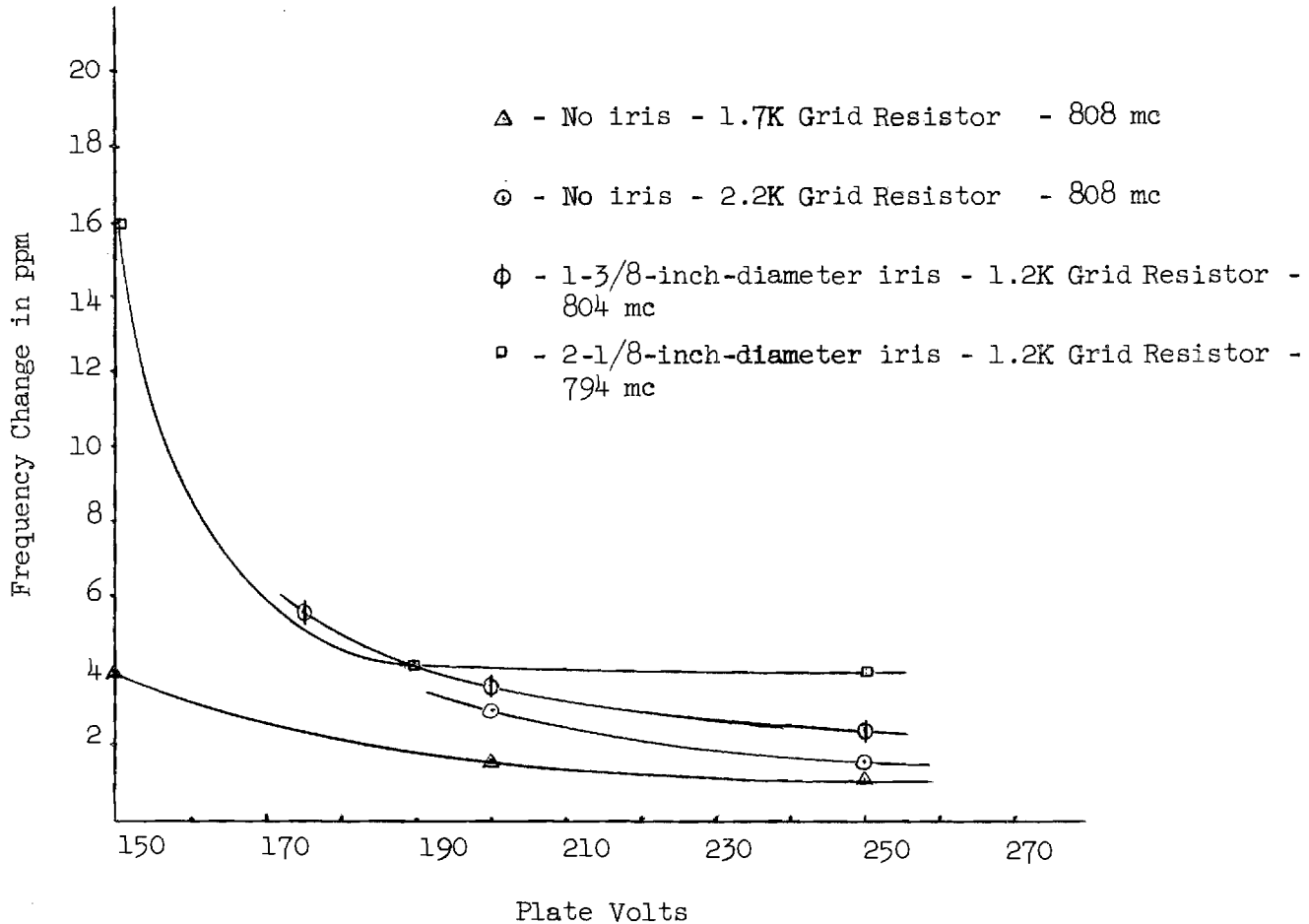


Figure 5.1. Results of Stability Tests on 800-Mc Oscillator.

A final test involved the effects of filament voltage. The filament voltage was changed in a single step by 0.3 volt from the normal level of 6 volts. First the circuit was completely stabilized, then an incremental change

was applied. There was an immediate decrease in frequency of 3500 cycles when the voltage was increased 0.3 volt, and approximately the same increase in frequency for an equal decrease in voltage.

C. External Cavity Control of Re-Entrant Type Oscillator

When the oscillator tube is connected to the high impedance end of the coaxial cavity, as is the case in the series-capacitor cavity-controlled oscillator and the re-entrant cavity type, the oscillations occur at a lower frequency than that of resonance of the cavity. The difference between this resonant frequency and the actual oscillator frequency is a measure of the instability of the oscillator. This is discussed in Progress Report No. 5 (2). For this reason it may be concluded that if an oscillator which is caused to oscillate at the exact resonant frequency of the cavity could be constructed, then it might be anticipated that very good orders of stability could be obtained.

The physical arrangement of the re-entrant cavity oscillator, with its plate-to-grid and grid-to-cathode lines, suggests several possible ways in which to connect an external cavity which may serve as the principal frequency-determining element. By proper arrangement the shortcomings resulting from connecting the oscillator by means of a loop which has leakage inductance can be virtually eliminated. Several suggested configurations are shown in the illustration in Figure 5.2.

In Figure 5.2A the external cavity utilizes the re-entrant cavity as the inner conductor and would represent a most compact configuration. The external cavity would be $\lambda/2$ in this case. A variation of this same type is shown in B. Here the $\lambda/2$ external cavity is placed adjacent to the oscillator. In C a $\lambda/4$ length external cavity is placed with its base against the re-entrant oscillator. A coaxial line terminated on each end by coupling loops is shown in D. The line length here determines the resonant frequency.

All of these methods of coupling the external cavities have the property of controlling the magnitude and phase of the feed-back between the grid-plate and the grid-cathode resonators. For this reason it would be desirable to have a re-entrant cavity arrangement which was just below the threshold of oscillation.

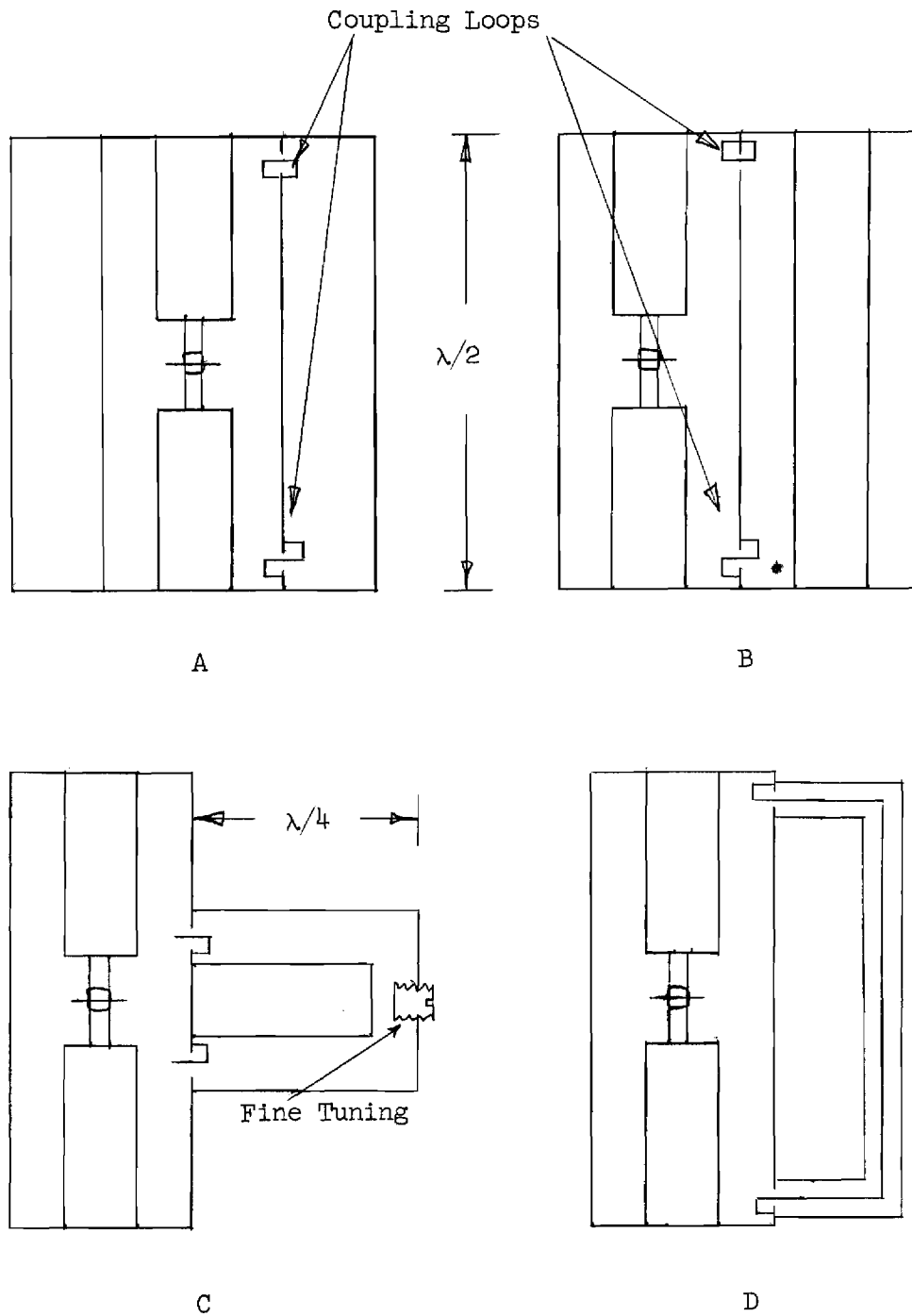


Figure 5.2. Possible External Cavity Feed-Back Arrangements.

The addition of the external cavity would then provide just enough feed-back of the proper phase to bring about oscillations. The external cavity presumably would then have control of the oscillation frequency. Since the coupling loops are not connected to the vacuum tube and are inside the re-entrant and the external cavity, a very low value of leakage inductance (self-inductance of loop) could be obtained.

A lumped equivalent schematic of the re-entrant cavity oscillator controlled by an external cavity is shown in Figure 5.3.

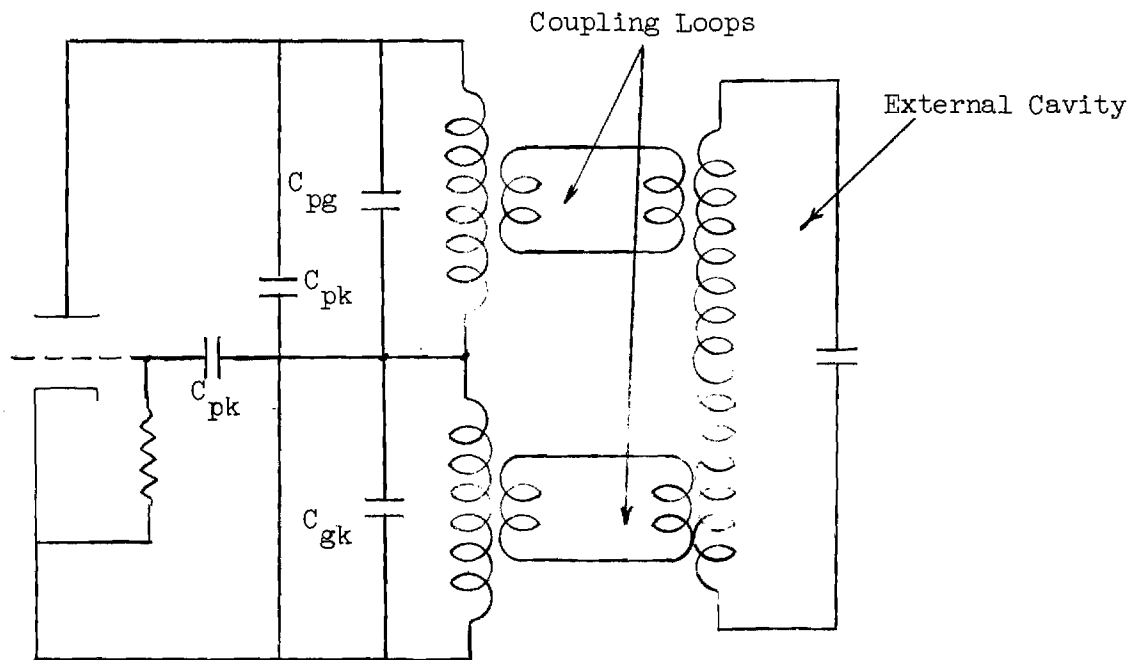


Figure 5.3. Equivalent Schematic of Re-entrant Cavity Oscillator.

The coefficient of coupling of all the coupling links should be equal to unity in order to avoid the objectionable leakage reactance which has been previously treated.

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Using materials at hand, i.e., the 650-mc, re-entrant cavity oscillator and a tunable quarter-wave-length cavity capable of a resonant frequency range between 600 and 700 mc, the configuration depicted by Figure 5.2C, was constructed. A flat surface to mount the external cavity against was milled on the re-entrant cavity outer conductor. The results of preliminary tests conducted on this setup were not very encouraging, presumably because of a number of factors. One disadvantage can be seen in the impedance ratios of the coupling loops. Inside the external cavity the loops are of very low impedance while the electric-field pickups in the re-entrant cavity are rather high. The circuit could not be made to oscillate by tuning the external cavity. If the circuit is made to oscillate before the connection of the external cavity, then a cessation of oscillation is experienced when the external cavity is connected and tuned to the oscillator frequency. For the moment work has been discontinued on this type of frequency control because of other more pressing work, but it will be reconsidered in the near future.

VI. TEMPERATURE EFFECTS ON CAVITY-CONTROLLED OSCILLATORS

In any study of the characteristics of oscillators it is highly desirable to isolate the individual factors which contribute to instability. These factors may include variations in anode and/or filament potential, changes in total space current and changes in ambient temperature. Variations in potential are usually significant factors in the frequency stability problem, however it is possible to stabilize the potentials of both anode and filament by regulated supplies and/or batteries. If the oscillator is of the cavity-controlled type and if adequate voltage stabilization exists, it may be found that the predominant factor causing frequency instability is variation in ambient temperature. This conclusion follows from the fact that the change in resonant frequency of a cavity is directly related to the expansion or contraction of its lateral dimensions (length of inner conductor in a coaxial cavity), and this in turn is precisely determined by the thermal coefficient of expansion of the material of which the cavity (or inner conductor) is composed.

The nickel-steel alloy known as Invar has been used extensively in cavity resonators, particularly because its coefficient of expansion is quite small. Invar has been utilized on this project as resonator material in cavity-controlled oscillators, but the effectiveness of resonator control has not been completely determined, at least as far as temperature effects are concerned. It has been considered important that the effects of temperature on and heat transfer within an Invar coaxial cavity be determined, hence a series of tests were recently instituted the results of which are being used to evaluate the rate of heat transfer and the effect of temperature upon the frequency of the associated oscillator. Considerable care has been given to the stabilization of potentials and currents in order that the desired variable and its effects may be considered as independent quantities. The results of the tests are described in the following paragraphs.

A. Effects of Temperature on Invar Cavity and Prototype

In an effort to evaluate the effect of temperature on oscillation frequency, an Invar and a prototype brass, cavity-controlled oscillator have been studied. It had been qualitatively observed on previous tests that the Invar, cavity-

controlled oscillators were not subject to a high rate of frequency drift even during the period from cold start to full warm up. However, a small amount of drift was observed over a long period of time, longer, for example, than was the case in brass cavities. This effect is due to the inherently lower thermal conductivity of the Invar. The c.g.s. conductivity for brass at room temperature is about 0.260, while that of Invar is about 0.025. The brass, then, has a conductivity of over ten times that of Invar. In addition, the specific heat of the Invar is about 30 per cent greater than that of brass, so that a greater quantity of heat is required to raise the temperature of an equivalent mass of Invar.

A frequency drift curve for an Invar, cavity-controlled oscillator all the components of which were initially at ambient temperature and to which anode and filament voltages were applied at zero reference time is plotted in Figure 6.1. There is seen to be a very rapid frequency drift during the first 5 minutes, a drift amounting to about 30 kilocycles. Thereafter the total drift is less than 14 kilocycles. The drift during the first five minutes is believed to be attributed to the changes in the vacuum tube and is an indication of the over-all stability of the oscillator. The drift thereafter is believed to be almost wholly due to the thermal coefficient of expansion of the Invar which is approximately 1 ppm/°C.

More evidence to support the above reasoning was observed from data taken on heat runs of an Invar cavity alone. An Invar cavity was constructed and immersed in the oven with thermocouples as shown in Figure 6.2. Using this setup, the oven was switched on, and the temperature was gradually raised for a period of over an hour while readings from each of the thermocouples were taken. The curves shown in Figure 6.3 indicate the rising ambient temperature. The lower temperature inside of the cavity is due to the thermal lag in the cavity material. The lag of temperature at the "outer" position is approximately 20 minutes behind that of the ambient for this particular rate of rise. It must be assumed that the temperature at the "outer" position would have an appreciable effect on the frequency of oscillation since this is at the top end of the inner conductor. In addition the tube is located at this position in the cavity.

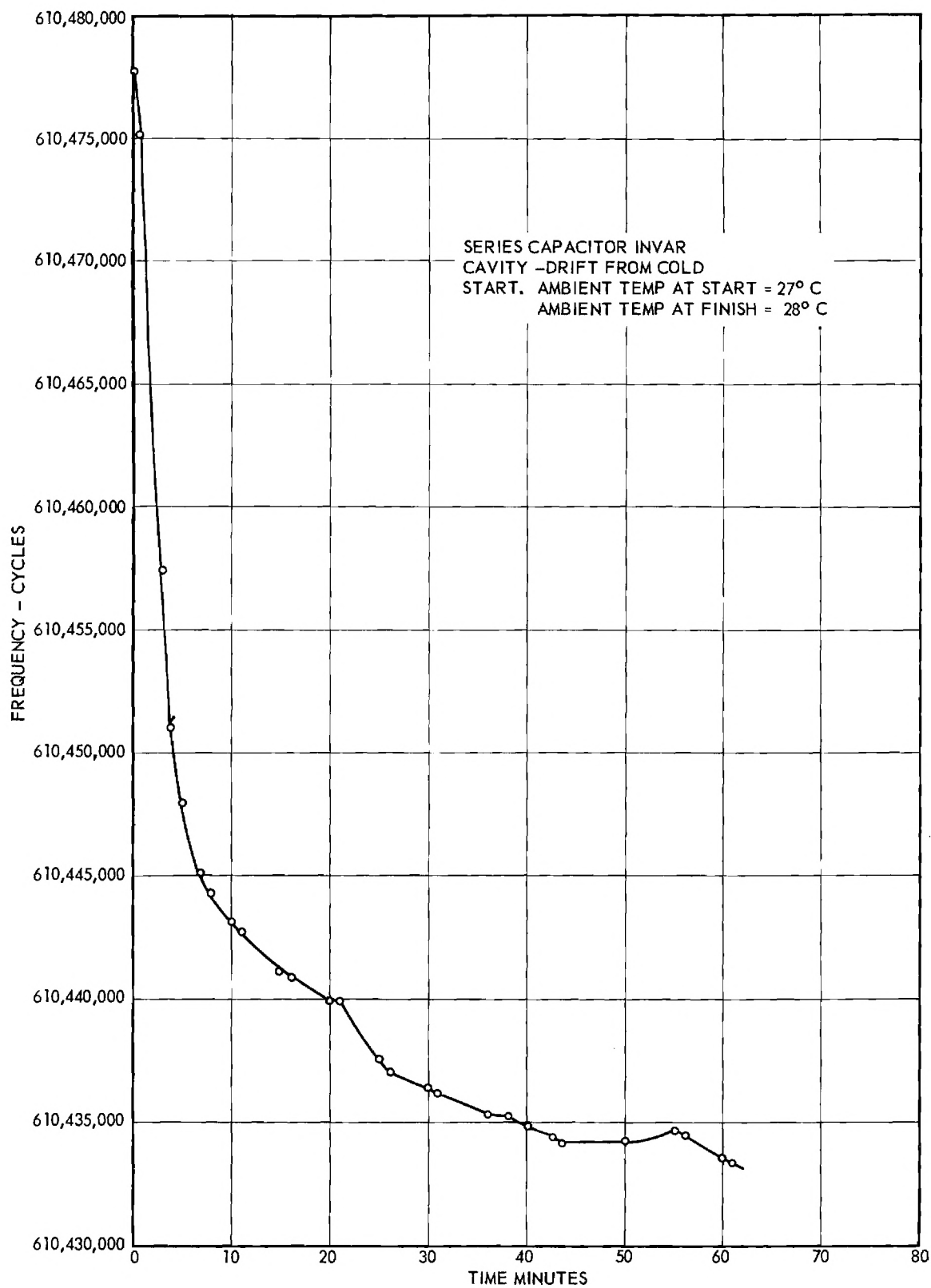


Figure 6.1. Frequency Drift of Series Capacitor Invar Cavity During Warm-Up.

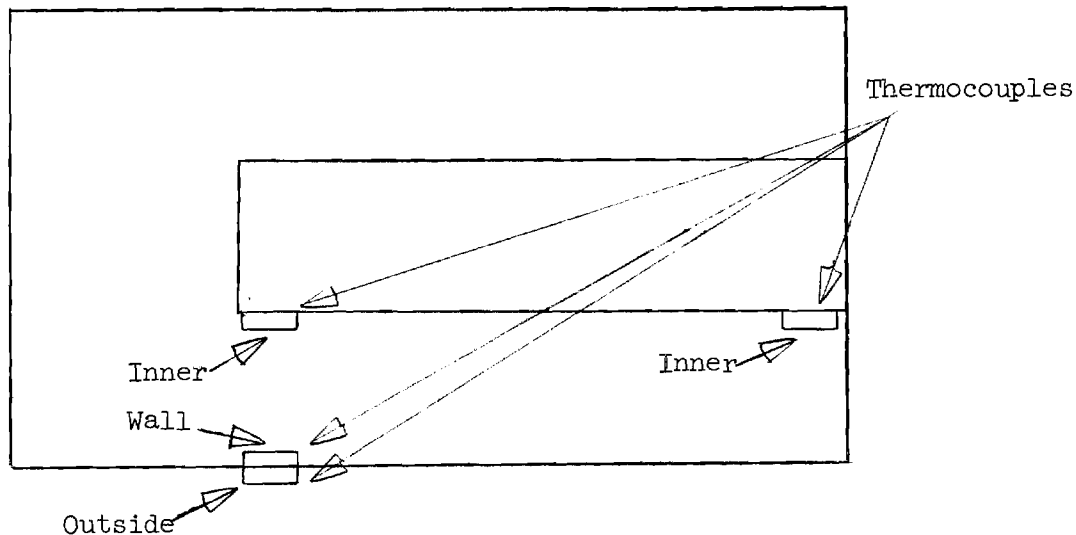


Figure 6.2. Thermocouple Positions in Invar Cavity.

Also of considerable interest is the temperature of the "inner" position, which is also on the inner conductor but at its base. This point is seen to be hotter than the "outer" position but still lags the "Wall" and "Outside" positions, a result of the heat conduction lag.

Another type of heat run was taken with the thermocouples in the same positions. This time the cavity was left at ambient temperature, and a 6AF4 vacuum tube was placed inside in the same manner as though the entire configuration was truly an oscillator. Plate and filament voltages were supplied to provide approximately the same power dissipation as would be expected in the oscillator, although no attempt was made to make this configuration oscillate.

The temperature-versus-time data are plotted in Figure 6.4 for this test. After the temperatures had reached an almost equilibrium condition, the oven was turned on and the outside ambient temperature was increased to an almost steady rise. During the first 75 minutes the "outer" position rose to an equilibrium condition of about 30°C higher than ambient, while the "wall" and "inner" position increased 11°C and 12°C respectively. The "outside" was only 7°C higher.

If one assumes that the frequency is determined entirely by the length of the inner conductor, thus neglecting "end" effects, it would be necessary to

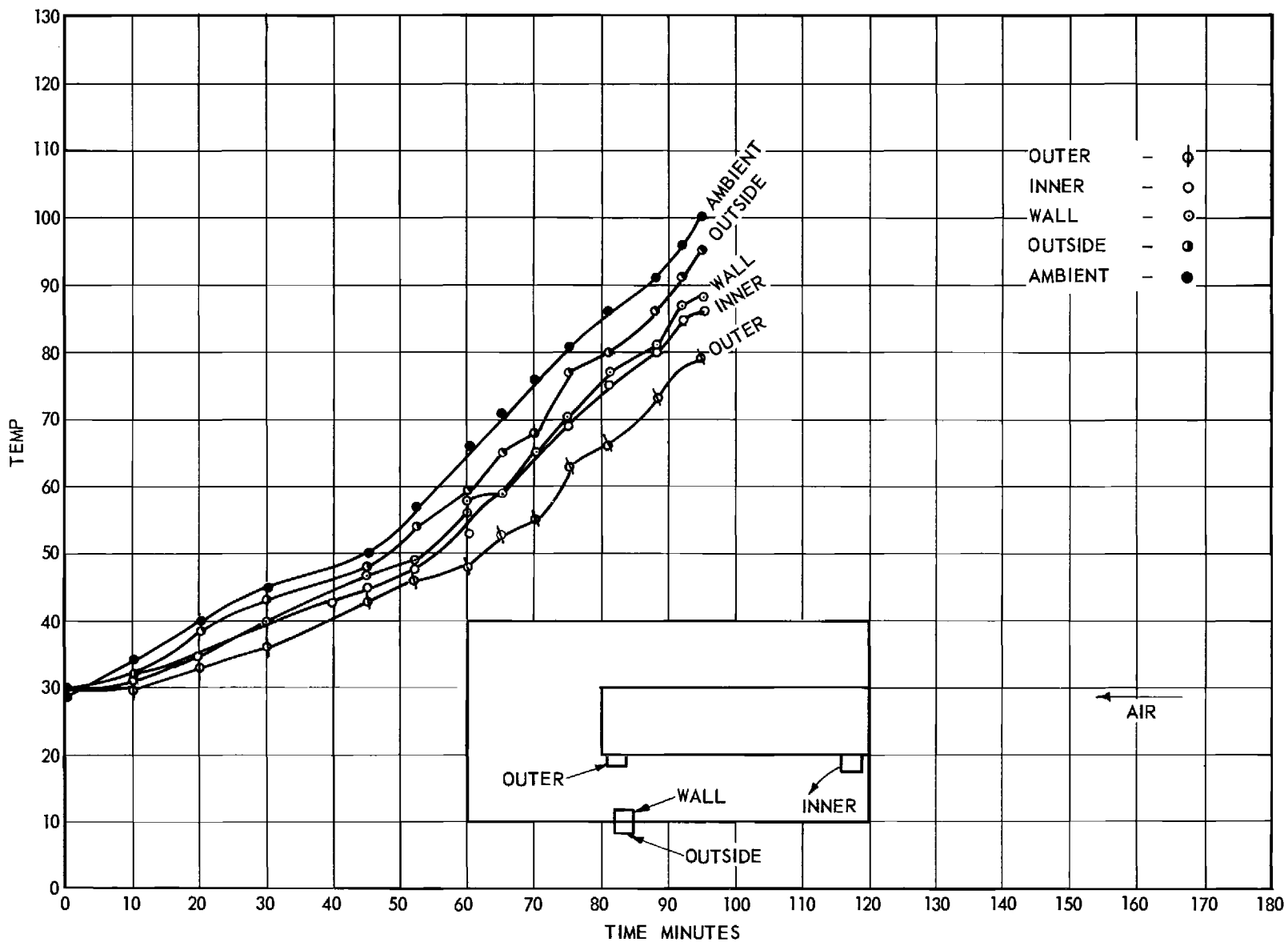


Figure 6.3. Effect of Ambient Temperature on Invar Cavity.

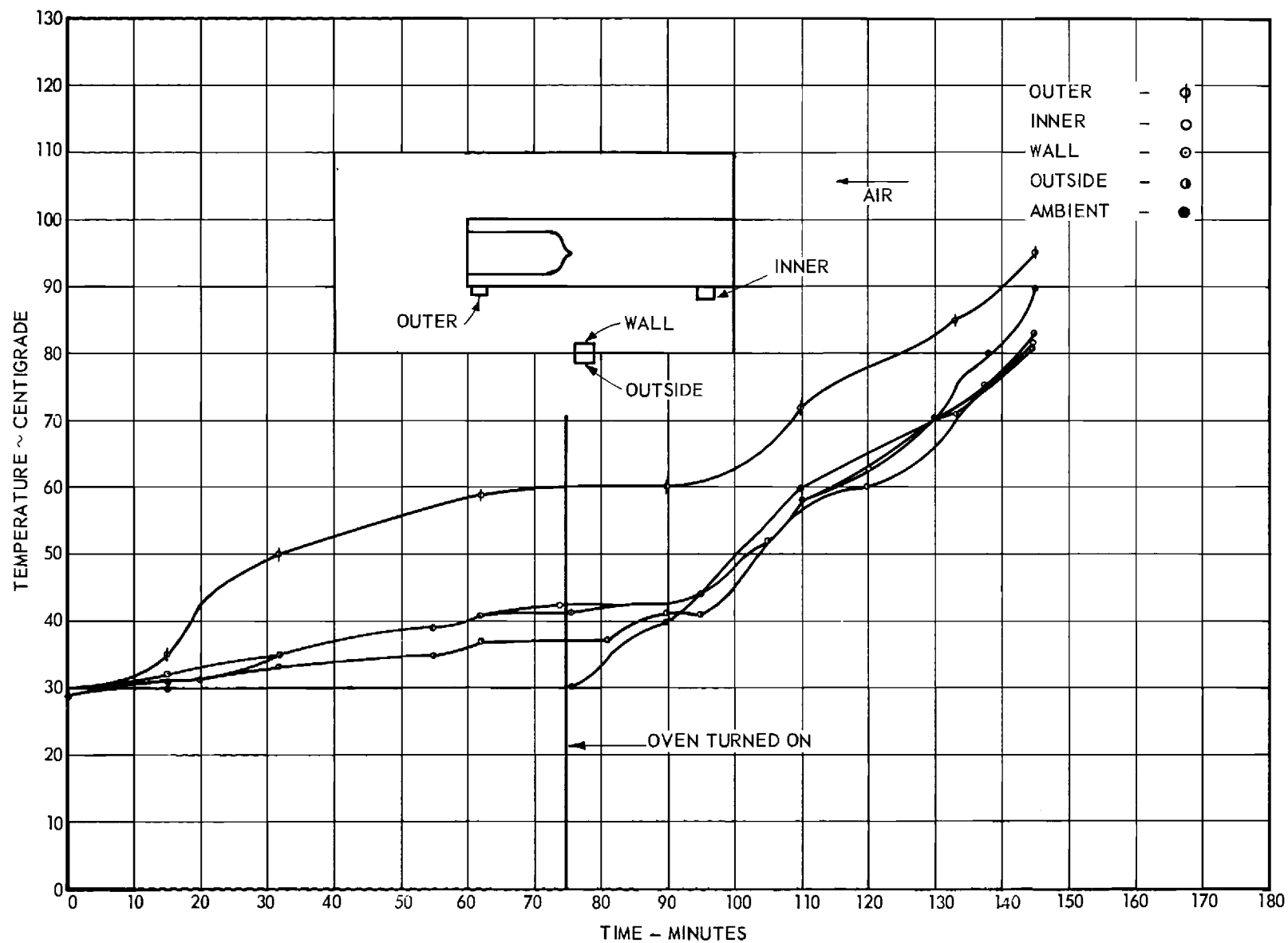


Figure 6.4. Effect of Ambient Temperature and Internal Heat on Invar Cavity.

integrate the temperature gradient of the inner conductor to determine the incremental length increase. An average temperature rise would be $\frac{30 + 11}{2} = 20.5$ degrees. This represents a frequency change of about 20.5 ppm or about 13 kc which corresponds approximately to the 14 kc observed in Figure 6.1, beginning at 5 minutes after initial application of potentials. This is represented by that portion of the curve to the right of the dotted line.

The oven was turned on after 75 minutes of operation, the change-over point being shown on the curve. The most significant conclusion reached here seems to be that the temperature of the inner conductor changed negligibly during the next 15 minutes even though the ambient rose 10°C during this time. The "outside" temperature did show a rise, however. A very interesting consequence of this condition was evidenced when an Invar oscillator, which had reached equilibrium temperatures at room temperature of 25°C, was suddenly immersed in an oven which had been maintained at 50°C for several hours. The frequency-versus-time data for these conditions are plotted in Figure 6.5. The surprising effect (noted on several attempts) is that the frequency rose initially to a maximum value and then after about 10 minutes dropped at a reasonable rate.

This effect is believed to be due to the fact that only the outer conductor temperature changes during the first 10 minutes, a condition illustrated in Figure 6.4, and that the expansion of the outer conductor lowers the capacitive end-effect. This condition is illustrated in Figure 6.6. As the outer conductor expands, and the inner conductor does not, the effect of this capacity is reduced, thereby raising the frequency of resonance. After ten minutes, however, the inner conductor begins expanding at a rate sufficiently great to overcome the outer conductor expansion, and there is finally seen to be a drop in the frequency, a drop which continues for two or more hours before equilibrium is again reached.

This effect was not experienced with a brass cavity of the same dimensions, probably due to the fact that the high heat conductivity of the brass allows very little lag between inner and outer conductor temperatures. In fact, if a fan moves air in the vicinity of the brass cavity, an immediate rate of drop in frequency is observed.

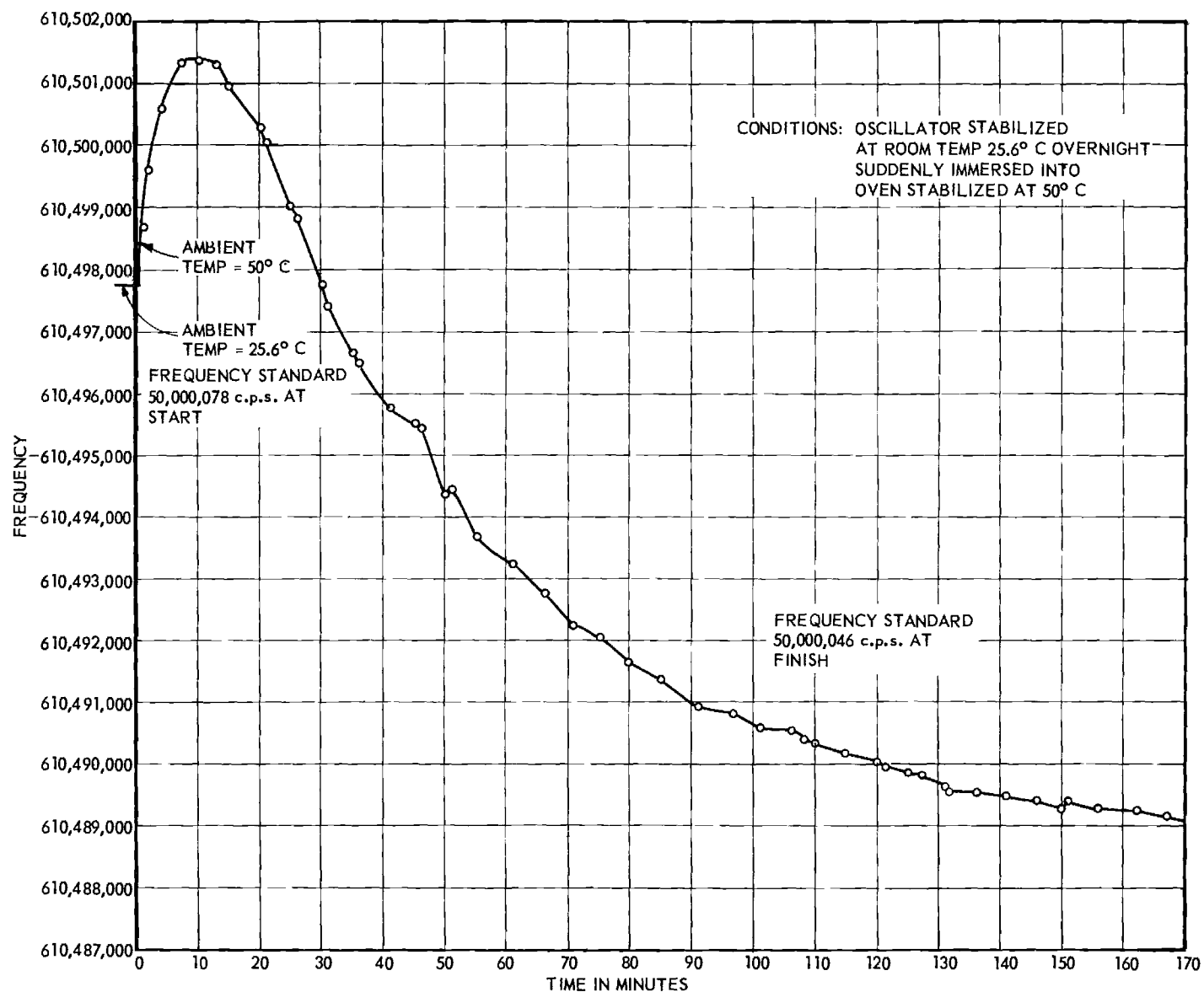


Figure 6 5. Effect of Abrupt Change of Ambient Temperature on Invar Cavity.

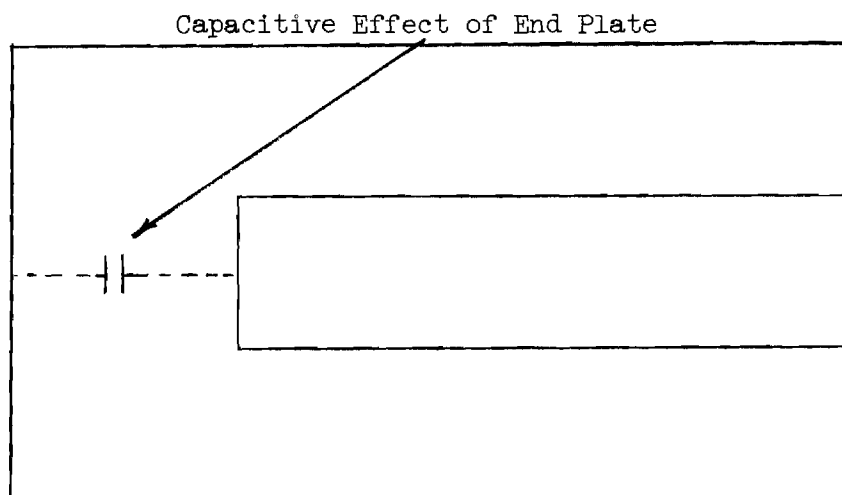


Figure 6.6. Capacitive Effect of End-Plate.

The brass, series-capacity oscillator was operated in the oven for a period of time while temperatures were stabilized. The results of these tests are shown in Figure 6.7. After being operated in an asbestos jacket overnight at room-temperature in an air-conditioned room, the cavity oscillator was placed in an oven, and the temperatures were stabilized at 41°C and later at 47.3°C . The asbestos jacket was, of course, removed. The brass-cavity oscillator seemed to stabilize or "level off" much quicker than the Invar. This was anticipated in view of the much higher heat conductivity of brass. The frequency change of 95 kc indicated for the first temperature change of 7°C is about 150 ppm. The expansion of the brass for 7°C would be about 140 ppm. For the next temperature change of 6.3°C the frequency change of 75 kc corresponds to about 120 ppm, while the brass would expand about $20 \times 6.3 = 126$ ppm. These rough calculations show that the frequency stability of the brass, cavity-controlled oscillator due to temperature changes is primarily a function of the expansion of the brass.

B. Effects of Small Filament Changes on Frequency of the Brass and Invar Cavity-Controlled Oscillators

A comparison of the frequency change of the brass and Invar cavity-controlled oscillators is seen in Figure 6.8. Here the oscillators had been stabilized at normal frequency with normal voltages applied to both plate and filaments. After application of a voltage increment the Invar cavity is seen to nearly stabilize at 2.5 ppm away from the original frequency, while brass, cavity-controlled oscillators show an immediate increase in frequency accompanied by a sharp drop which continues at nearly a linear rate for a considerable length of time. The data presented here were taken for 27 minutes on the brass, cavity oscillator, and no sign of a "level off" is seen at 6.5-ppm frequency change.

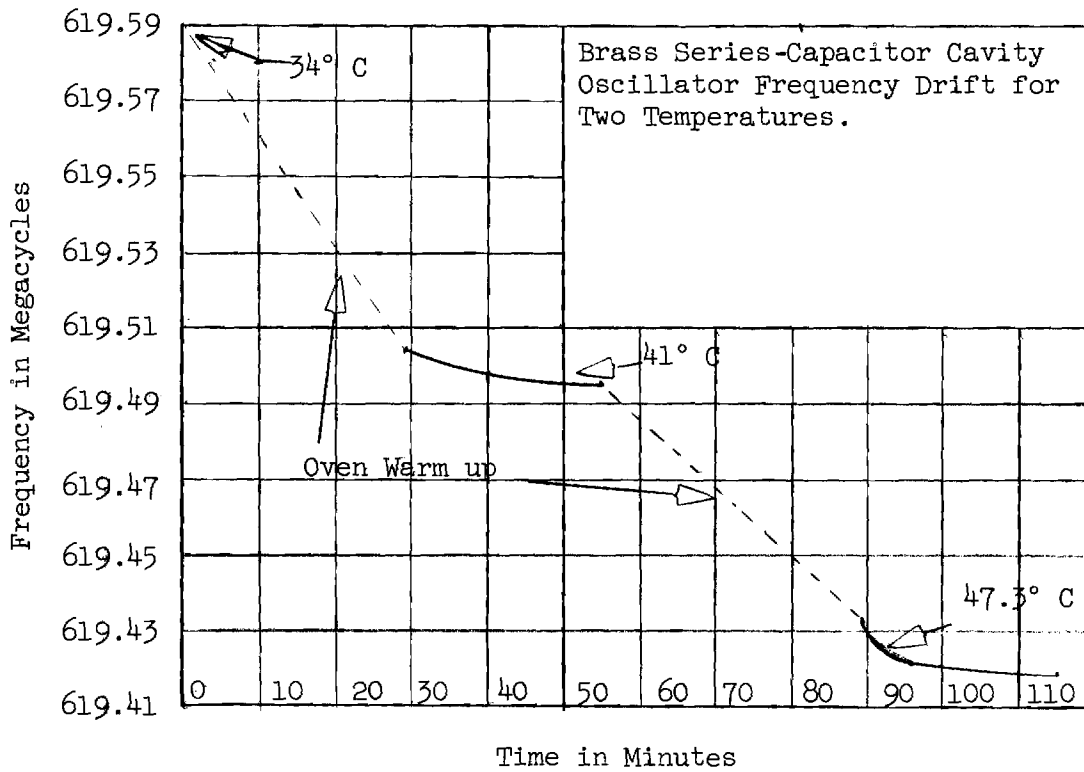


Figure 6.7. Temperature Effects on Brass, Cavity-Controlled Oscillator.

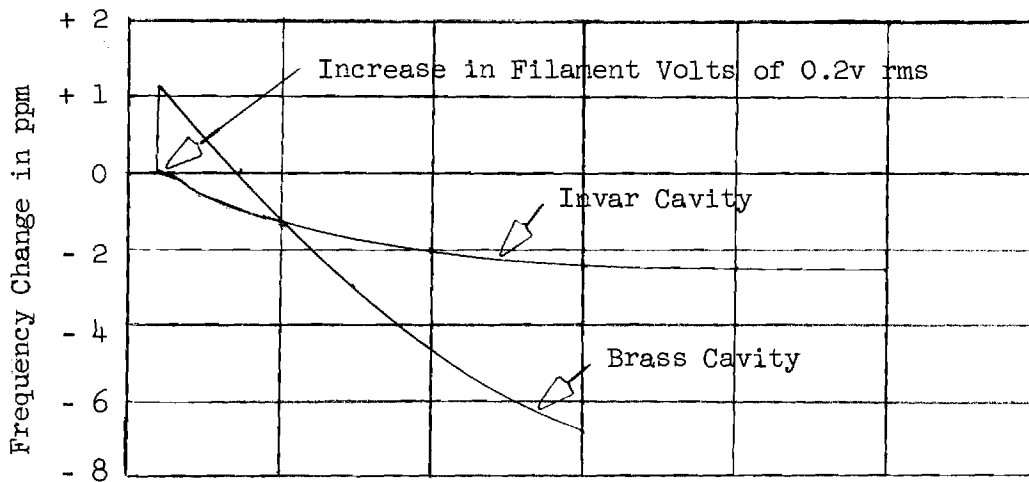


Figure 6.8. Comparison of Filament Voltage Effects on Brass and Invar Cavities.

VII. CONDUCTIVE COATINGS ON CERAMIC BASES

In early reports (3,4) submitted under the present contract, reference was made to electrical resonators which were designed to employ ceramic materials as bases for conductive coatings. These resonators were to have both excellent electrical characteristics and small temperature sensitivity. Certain ceramics, notably one designated by the trade name of Stupalith, exhibit thermal coefficients of expansion which approach a claimed value of zero. It is therefore evident that the successful utilization of such a ceramic in an electrical resonator should greatly reduce the temperature sensitivity of an oscillatory system, particularly if the resonator is the primary frequency-determining element.

In the earlier work a conductive coating was established by spraying and firing at high temperature conductive silver paints, such as DuPont No. 4760 silver paste, which are designed to adhere to ceramic bases. Electroplated silver films complete the coatings and permit development of a finely polished surface.

Such ceramic base conductors proved to be unsatisfactory for reasons which are as follows. First, there was definite evidence that the ceramic, somewhat porous in the specimens tested, retained residual gases within its cellular structure. Application of heat, either localized or high ambient, resulted in the formation of bubbles under the silvered surface with resulting distortion or actual fracture of the silver film. Second, the mechanical strength of the ceramic appeared insufficient to withstand localized stresses. Attempts to establish firm union of two such ceramic bodies often ended in complete fracture of a surface, or surfaces. These surfaces, in fracturing and pulling away from the main body, were found to have ceramic material adhering to the under surface.

As a result of the failures cited, investigations were discontinued. Recently, however, new approaches to the problem have been considered and some preliminary steps have been taken to determine their practicability. One of these methods is designed to coat the ceramic with a smooth, firmly adherent glaze which in turn serves as a base for conductive coatings. The other method employs an ion-bombardment and sputtering technique which places a metal coating directly upon the ceramic. These methods are described in some detail in the following paragraphs.

A. Vitreous Coating with Small Expansion

The porosity of ceramics such as Stupalith and its effect upon the adherence of metal films should theoretically not be a problem if a thin, smooth glaze could first be established to cover the base material. However, most standard compositions from which glazes are formed have a thermal coefficient of expansion of several parts per million per degree centigrade. When applied to a low expansion body the extreme differential in expansivity results in crazing or devitrification.

A recent set of experiments designed to produce a satisfactory glaze for low expansion bodies has been conducted and reported on by the Titanium Alloy Mfg. Co. (5). A very large number of compositions were tested, with varying results. However, in all cases it was observed that all compositions containing manganese dioxide showed profound advantages in reduction of crazing over all the other possibilities. This was true whether or not the firing temperature was low or high. However, it is evident that glazes of low melting points should be more satisfactory because of the relative smaller differential of expansion.

The information supplied by the reference cited (5) has been utilized on this project in an effort to render Stupalith satisfactory for use in electrical resonators. The most satisfactory process determined to date is outlined below:

- a. The basic material was in all cases a composition of 12 per cent B_2O_3 and 88 per cent PbO . To this was added approximately 5 per cent MnO_2 . The resulting composition has been shown to have a coefficient of expansion of about 2.2 ppm/°C.
- b. The material was smelted at 1200°-1500° F, fritted in water, dried and milled with 10 per cent clay.
- c. A water suspension of the resulting material was then formed, and the ceramic material was dipped in it. The body was then fired at 1400° F for 15-20 minutes.

The glazed bodies resulting from the steps outlined above have been found to exhibit certain desirable properties and also some undesirable ones. The glaze has in all tests indicated a firm adherence to the ceramic and exhibits very slight evidence of crazing. However, the resulting surface is less smooth

than was the original ceramic, with evidence of mounds and craters. These imperfections are reproduced essentially without change when a conductive silver coating is applied over the glaze.

At present the required conductive coating cannot be obtained from fired silver pastes, as had been the previous procedure, because the relatively low melting point of the glaze will not permit firing at required temperatures of 1200°-1400° F. In lieu of this method a sputtering process has been successfully applied by which a silver film is added over the entire surface. To this base film electroplated silver may be added.

Several samples have been subjected to glazing and subsequent sputtering. All exhibit undesirable roughness of the surface film. On the other hand, it appears that the surface has sufficient mechanical strength to eliminate the fractures described in the previous pages. The samples thus far treated are too small to be used in resonators, in fact further testing is awaiting delivery of new pieces of Stupalith. However, it is planned to apply the process described to a ceramic rod of proper size in order to form the center conductor of one or more coaxial-cavity resonators on hand. By testing these units it may be determined if the indicated mechanical strength will eliminate the early failures and also whether or not the unavoidable surface roughness will seriously effect the cavity Q.

B. Direct Sputtering of Conductive Coatings

As an alternative to the process just described it has been found that a metal coating with considerable mechanical strength can be applied directly by a sputtering process. A sample of Stupalith which gives promise of developing satisfactory resonator material was subjected to the following treatment:

- a. Scrubbed with detergent, water rinsed, dried at moderate temperature in drying oven.
- b. Cleaned by ion-bombardment.
- c. Sputtered with nickel to form a film a few hundred angstroms in thickness.
- d. Electroplated with silver to thickness of about 0.001 inch.

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The product of this process has considerable mechanical strength as was evidenced by soldering pieces of wire to the surface. These pieces adhere firmly, and fracture of the surface film cannot be effected except by application of relatively extreme pressure. If this condition of surface strength is found in all samples, it is believed that reliable mechanical and electrical joints can be achieved in electrical resonators.

Unfortunately, the process described, like the glazing process, produces a surface which is somewhat rougher than that of the ceramic base. Some improvement may possibly be effected by further plating and polishing but a "mirror-finish" is not contemplated. Further tests in finished resonators should determine if the residual roughness seriously affects the electrical quality of the sample.

No fixed conclusions can as yet be reached pertaining to the potentialities of these low-expansion ceramics when given conductive coatings by either of the mentioned processes. However, the attractive temperature characteristics are considered to be of sufficient worth to warrant considerably more investigation. Accordingly it is planned to extend the tests upon receipt of the samples of Stupalith now on order.

VIII. CONCLUSIONS

A frequency-measuring system which has been completed in basic form during the present quarter now permits accurate determination of all frequencies from audio through several thousand megacycles. Measurements recorded in the 500-800-mc region indicate that errors in measurement are not worse than three parts in 10^8 . These errors can be reduced to one part in 10^8 , if necessary.

A series of tests on three 600- and/or 800-mc, cavity-controlled oscillators show that the effect of slow changes in ambient temperature can be closely predicted by the coefficient of expansion of the inner conductor of the coaxial cavity. This is true for both brass and Invar cavities. The effects of rapid changes in ambient temperature are quite different, the Invar cavity exhibiting anomalous frequency deviations due apparently to the extremely slow rate of heat transfer in this particular nickel-steel alloy.

New investigations of ceramic materials for use in electrical resonators have shown that two previously untried processes may permit the attachment of a satisfactory conductive coating to ceramics. The first involves application of a glaze whose purpose is to form a smooth adhesive base for fired-silver coatings. The second employs ion-bombardment and metallic sputtering to place a metallic coating directly upon the ceramic. Each method is to be the subject of further investigation.

IX. PROGRAM FOR THE NEXT QUARTER


Primary attention will be devoted toward concluding measurements on already assembled, cavity-controlled oscillators. The 1000-mc, re-entrant type oscillator with pencil triode will be subjected to tests equivalent to those discussed in this report.


The general problem of optimizing frequency stability in the re-entrant type cavity will be the subject of considerable study. The addition of feed-back methods which might emphasize phase-shift effects will be included as a subject of investigation.

Methods of placing firmly adherent conductive coatings on ceramic materials will be further investigated. Emphasis will be directed toward determination of a process by which the surface roughness evidenced in present techniques may be eliminated.

Considerable time will be devoted during this quarter to the preparation of a final report. This report will summarize the results of 24 months of investigation.

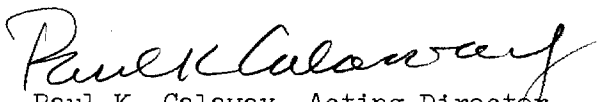
Respectfully submitted:


Donald W. Fraser
Project Director


Edward G. Holmes
Research Engineer

Approved:


J. E. Boyd, Head
Physics Division


Paul K. Calaway, Acting Director
Engineering Experiment Station

X. IDENTIFICATION OF KEY TECHNICIANS

This project is under the direction of Mr. Donald W. Fraser who devotes one-third time to this work at present. He is Assistant Professor of Electrical Engineering at Georgia Tech and holds the degree of Master of Science in Electrical Engineering from this institution. He worked on station project 131-45, "High Frequency Crystal-Controlled Oscillators," devoting approximately one-fourth time to it. His other experience includes five years of electronic testing and research in the U. S. Navy.

Mr. James C. Sellers joined the project as Electronics Technician at its onset. He is concurrently devoting full time to the project. Mr. Sellers previously was engaged for eight years in nuclear instrumentation with the AEC at Oak Ridge, Tennessee, where he had extensive experience as a technician in the design, assembly and testing of electronic circuits.

Mr. Edward G. Holmes continues to work on the project. Mr. Holmes holds the degree of Master of Science in Electrical Engineering. His experience in the electronics field includes five years of work with frequency-measuring apparatus and broadcasting equipment, two years as Electronics Officer in the U. S. Navy and three years of research and development work in UHF and microwave equipment. He is now devoting full time to the project.

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ENGINEERING EXPERIMENT STATION
of the Georgia Institute of Technology
Atlanta, Georgia

FINAL REPORT

PROJECT NO. 229-198

PRECISION FREQUENCY CONTROL TECHNIQUES
(500 Mc and Higher)

By

DONALD W. FRASER AND EDWARD G. HOLMES

- o - o - o - o -

CONTRACT NO. DA-36-039-sc-42590

DEPARTMENT OF THE ARMY PROJECT: 3-99-11-022
SIGNAL CORPS PROJECT: 33-142B

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NOVEMBER 1, 1954 to APRIL 30, 1955

PLACED BY THE U. S. ARMY
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FORT MONMOUTH, NEW JERSEY

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I. PURPOSE

The purpose of this project was threefold: (a) to continue work on stabilization of oscillators between 500 and 3000 mc, using cavity resonators, (b) to continue to work on frequency control utilizing high-order overtones of quartz-crystal blanks and (c) to undertake any other investigations which may arise during the course of the work outlined in (a) and (b) above, or which may be mutually agreed upon between the Contractor and the Contracting Officer or his representative.

By agreement with the sponsor, investigations of resonances below 500 mc might be prosecuted as preliminary steps in determining the feasibility of frequency control by the phenomena under study. In addition, cavity resonators previously under construction and designed to provide control of frequencies below 500 mc might be completed and tested as aids in perfecting measurement techniques which will later be applied to the range of frequencies above 500 mc.

II. ABSTRACT

This report contains all the important aspects of the seven previous progress reports and coordinates a number of subjects which previously appeared isolated and detached. In addition, experimental and theoretical work which was accomplished in the final quarter is presented.

Primary attention has been devoted to the design, construction, and testing of coaxial-cavity resonators, and particular emphasis has been placed upon methods of rendering these cavities insensitive to temperature variations. A description of several resonators which have attained low-temperature sensitivity by means of compensation or by use of materials of low expansivity is presented in Chapter IV. The application of similar resonators as frequency controlling elements in UHF oscillators operating in the frequency range above 500 mc and preferred methods of soldering component parts into firmly bonded, airtight packages are discussed in Chapter VI.

The remainder of the report is devoted to a compilation and coordination of numerous topics which appeared in somewhat isolated forms in various progress reports. A summary of investigations in such fields as automatic frequency control and synchronization of oscillators and brief comments upon other types of frequency control which have appeared in the literature are presented in Chapter VII. The body of the report is completed with an outline of the methods of measurement which have been used to determine the characteristics of the cavities.

III. INTRODUCTION

A. History of the Contract

This project, entitled "Precision Frequency Control Techniques (500 mc and Higher)," was sponsored by the Signal Corps, U.S. Army, through the Squier Signal Laboratories, Fort Monmouth, New Jersey. The initial contract was numbered DA-36-039-sc-42590 and work started on this project on February 1, 1953. The number 229-198 was assigned to this project by the Georgia Institute of Technology. An extension of the original contract for a period of one year was received in February 1954. At the request of the contractor, the termination date was delayed until April 1, 1955, and the delivery date of the final report was delayed until April 30, 1955.

B. Objectives and Methods of Approach

As stated in the "Purpose" one of the general objectives of this project was to continue work on stabilization of oscillators between 500 and 3000 mc, using cavity resonators. Through decisions reached in conferences with the sponsors, it was agreed that major emphasis should be given to investigations of methods of producing hermetically sealed temperature-insensitive cavities having firmly adherent plated surfaces.

Investigations of possible means of constructing cavities with low temperature sensitivity indicated that each of two methods could potentially produce a resonator which would not be subject to expansion. One method involved a compensation process between two materials of unlike expansivity, the other would employ a material, Stupalith, which has a claimed zero coefficient of expansion. Both methods were applied, and cavities with small expansivity have been produced.

The compensation principle is essentially satisfactory only at a single frequency, hence considerable emphasis was directed toward utilization of low-expansivity materials in non-compensated cavities. The nickel-steel alloy, Invar, has attractive characteristics and was utilized for inner and outer conductors of coaxial cavities with the objective of producing a resonator which would be virtually insensitive to rapid changes in ambient temperature and moderately insensitive to long-term changes.

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The investigation of cavity resonators included studies of possible means of designing and assembling cavity-controlled oscillators of high stability. A variety of forms of oscillators, including types in which the vacuum tube is exterior to the cavity and types in which it is interior, were constructed and tested.

Other methods of frequency control at UHF were investigated in less detail. These methods included forms of automatic frequency control, synchronization of oscillators, and employment of overtone responses of piezoelectric quartz resonators.

Finally techniques of measurement at UHF were explored in some detail. The literature reveals many and diverse methods of measurement of frequency impedance and allied parameters. A section of this report has been devoted to those methods of measuring frequency and cavity characteristics which have been adjudged by the technicians to be the most accurate.

IV. COAXIAL-CAVITY RESONATORS

A. Introduction

Numerous devices are presently in use as resonator elements in UHF oscillator and frequency-control circuits. Among these devices may be named such configurations as the Split-Cylinder Resonator, the Modified-Semi-Butterfly-Tuner, and the Distributed-Inductance Line. These and similar types are usually designed for the purpose of obtaining a broad tuning range, but are not, in general, to be relied upon to give precision frequency control.

In the microwave region, the resonant cavity has been found to be successful as a measuring tool and as a frequency-controlling element. Its principal advantages include almost perfect shielding from external r-f fields and very high orders of quality factor (Q). Moreover, the Q may normally be improved by filling the cavity with a dry inert gas. A cavity constructed of low-expansivity materials results in a device which is relatively insensitive to ambient-temperature variations.

A cavity which is resonant in the UHF region is large but would compare favorably in size with the combination of a very stable low-frequency crystal oscillator succeeded by a chain of multipliers to produce the same UHF output frequency. The coaxial cavity operating in the dominant (TEM) mode, however, can be made considerably smaller. This reduction in size is not without cost since the magnitude of the obtainable Q is reduced. The theoretical Q of a representative copper coaxial quarter-wave cavity operating in the TEM mode at 1000 mc would be about 18000. The Q of a cylindrical cavity adjusted to the same frequency and operating in the TM_{010} mode would be nearly 50000.

The outside dimensions of the 1000-mc coaxial cavity could be 3 inches in diameter and 4 or 5 inches in length. These figures represent the size consistent with generation of only the TEM mode. The 1000-mc TM_{010} cavity, on the other hand, would be almost 12 inches in diameter and 1 or 2 inches in length. This comparison shows that the coaxial cavity represents a saving in volume of at least 3 or 4 to 1 while exhibiting a Q reduction of only less than 3 to 1. In practice, excellent orders of stability have been obtained with the coaxial cavity, in the UHF region, and the increase of Q by means of the higher mode cavities is not usually warranted.

It has been shown in a previous report (1) and elsewhere that the frequency-controlling ability of a resonator can be gauged by its Q . That is to say that the higher the Q the greater the phase change for a given frequency change. Moreover, the susceptance or reactance change will be greater for a given frequency change. It is desirable, then, to build the resonator with a high Q so that it will be highly sensitive to frequency variations but be insensitive to surrounding physical conditions, such as temperature and humidity.

The Q of a coaxial cavity is given approximately by (2)

$$Q = 8.39 \sqrt{f} b H^2 \quad (4.1)$$

where b is the outer diameter in meters, f is the frequency in cycles and H is a variable dependent upon the ratio of the outer to inner conductors. Values of H appear in reference 2 and are also shown in Figure 4.1. The maximum value of H is unity and occurs when the ratio of the diameters is approximately 3.6.

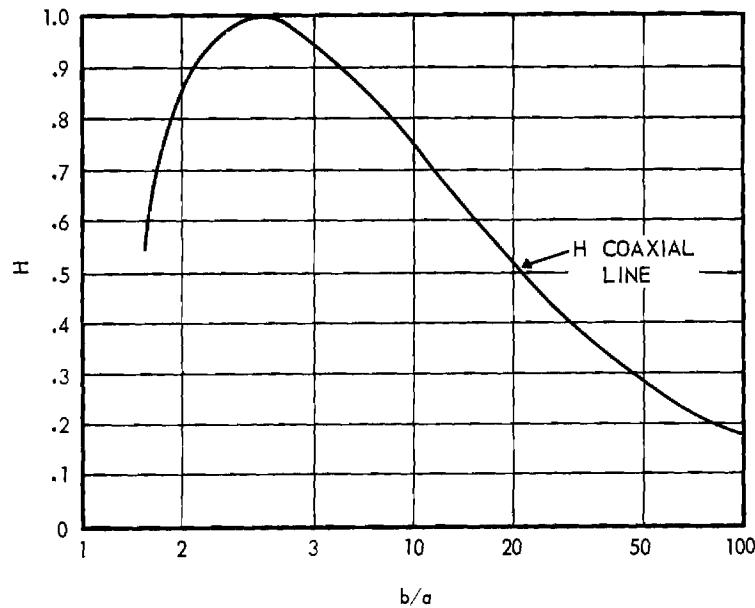


Figure 4.1. Values of the Parameter H .

It is seen that the Q is directly proportional to the outer diameter when the ratio of the diameters is constant. The limiting factor is not only the

physical size, but the generation of higher order modes if the diameter is made too large. In general, no higher order modes will exist if

$$\lambda > \pi (b + a) \quad (4.2)$$

where b and a are the outer and inner diameters of the cavity, respectively, and λ is the free space wavelength of the frequency of operation. If $b/a = 3.6$, then (4.2) becomes

$$\lambda > 1.28 \pi b \quad (4.3)$$

or approximately

$$\lambda > 4b \quad (4.4)$$

Under conditions of optimum Q, i.e., $b/a = 3.6$, b may be made slightly less than a quarter-wave length for the largest value of Q obtainable while precluding the possibility of higher modes.

Substitution of the value of b found in (4.4) into (4.1) gives

$$Q = \frac{8.39 cH}{4 \sqrt{f}} \quad (4.5)$$

where c is the velocity of light in the dielectric. Thus, if the frequency is reduced by four, the Q is doubled, but the volume of the cavity is increased 64 times. For this reason, cavities are, in general, designed for optimum Q consistent with space requirements.

B. Materials Used in Construction of Coaxial Cavities

The usual coaxial cavity is physically constructed as shown in Figure 4.2. The inner conductor is made equal to approximately $\lambda/4$ while the outer conductor is made somewhat longer to provide a "overhang" beyond the inner conductor. This "overhang" region is a circular waveguide operating beyond cut-off if the proper design parameters are used. If this section of the cavity is made sufficiently

long, very little error is introduced by cutting the inner conductor to exactly a quarter-wave length at the resonant frequency. If the "overhang" must be made short because of space or material limitations, there is a capacitance effect to the end plate which appears in shunt with the high-impedance end of the cavity as shown in Figure 4.1. This capacitance is given by (3)

$$C = \frac{a}{30 \pi v} \left[\frac{\pi a}{4d} + \ln \frac{(b - a)}{d} \right] \text{ farads} \quad (4.6)$$

Where v = velocity of propagation in the cavity dielectric. This quantity must be considered when calculating the resonant frequency of the cavity.

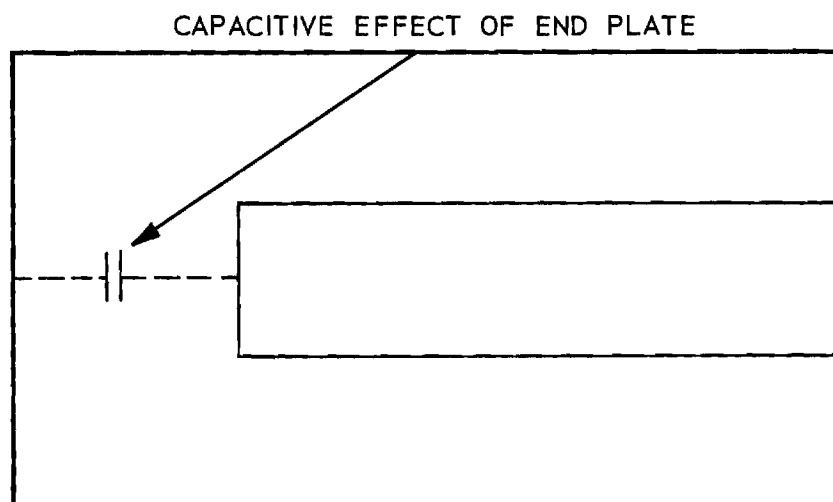


Figure 4.2. Typical Form of a Coaxial Cavity.

One of the most common cavity materials is brass, principally because of its excellent rigidity and machinability. In addition, it can be easily silver plated to give a highly conductive surface. Its chief disadvantage is its high expansivity--about 20 ppm/°C. Because of its high expansivity, its high heat conductivity also becomes a disadvantage since heat is transmitted throughout its volume very rapidly.

On this project, brass resonators have been used, because of the advantages cited above, to test prototype designs. Other types of cavities have been investigated for the purpose of reducing the temperature sensitivity. These are described in detail in the following paragraphs.

C. Cavities Investigated and Their Characteristics

1. Compensated Coaxial Cavities

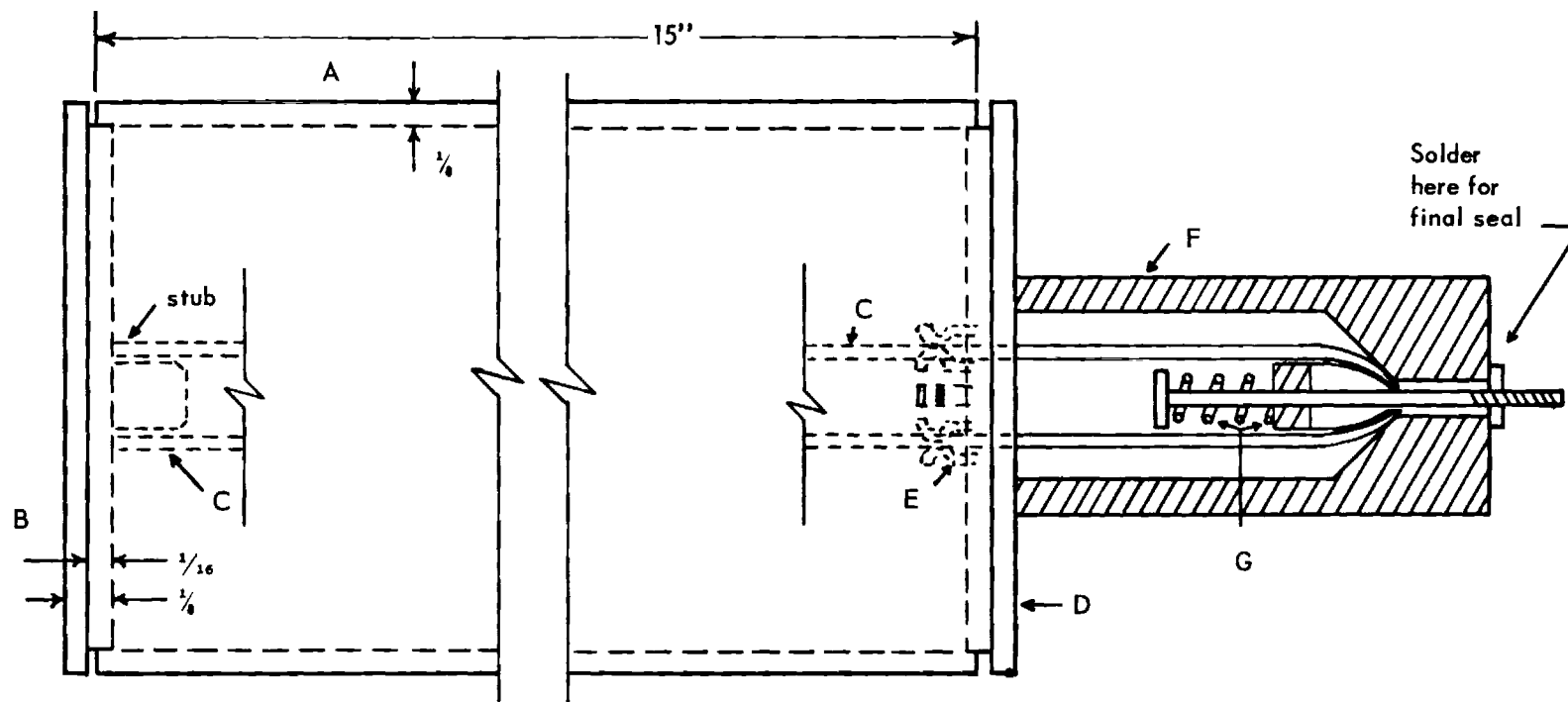
Compensated coaxial cavities utilize a principle by which the unequal expansivities of two materials are employed to neutralize the normal effects of thermal expansion upon the inner conductor. Those cavities constructed in the course of the present investigation employed outer conductors made of brass and inner conductors formed from silver-plated Pyrex and Invar. The inner conductor extended into an extra (compensating) section of brass. One of the earlier models of this type is shown in Figure 4.3.

The length of the compensating section is equal to the product of the length of the inner conductor and the ratio of the expansivities of the materials used for the inner and outer conductors. The inner conductor shown in Figure 4.1 is formed of Pyrex and is supported mechanically at both ends. It is silver plated over a portion of its length. Electrical contact to the shorted end of the cavity is made by silvered finger contacts which permit axial motion required in the compensation process.

Although the experimental tests conducted on the cavity indicated that the effective frequency of resonance of the cavity was essentially unchanged by variations in ambient temperature which occur slowly, an apparent thermal lag was observed when the cavity was subjected to rapid heating or cooling. This effect is perhaps caused by the equal mass-to-area ratios of the resonator proper and of the compensating section. The results of these tests are indicated in Figures 4.4 and 4.5.

Figure 4.4 illustrates the first three runs during which temperature excursions were held within an upper limit of 70° C. In each of these cases, a fairly uniform rise of frequency versus temperature is evident. The same is true in the fourth run, but in the fifth and last, the upper temperatures were reached rapidly by forced heating. A reverse slope is found in the 65° to 85° C region. This effect was apparently due to the thermal lag.

The data for the curves of Figures 4.4 and 4.5 were taken within a ten-day period. The cavity was then removed from the test bench and placed upon the



Assembled view, consisting of following units:

- A. Hollow Tubing 15" long, 1 3/4" O.D., 1 5/8" I. D. (Brass)
- B. End Plate, 1/8" Brass with stub support for Pyrex tubing
- C. Pyrex tubing, silver plated 24.5 cms from end plate D
- D. End plate E. Beryllium copper, silver plated, contact fingers
- F. Pressure sealing cap (in cross section)
- G. Spring and flexible pressure transfer section

Figure 4.3. Temperature-Compensated Brass Resonator.

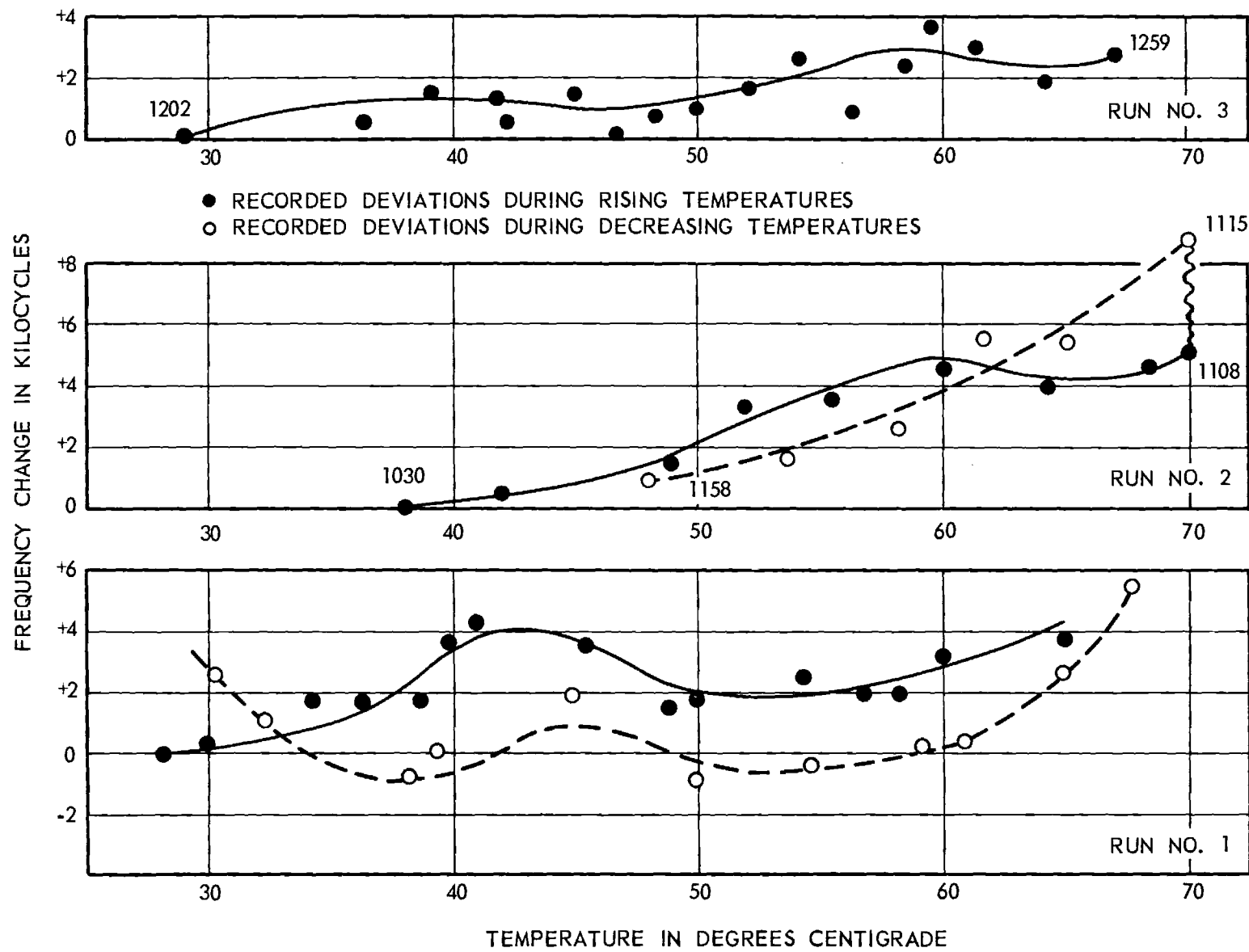
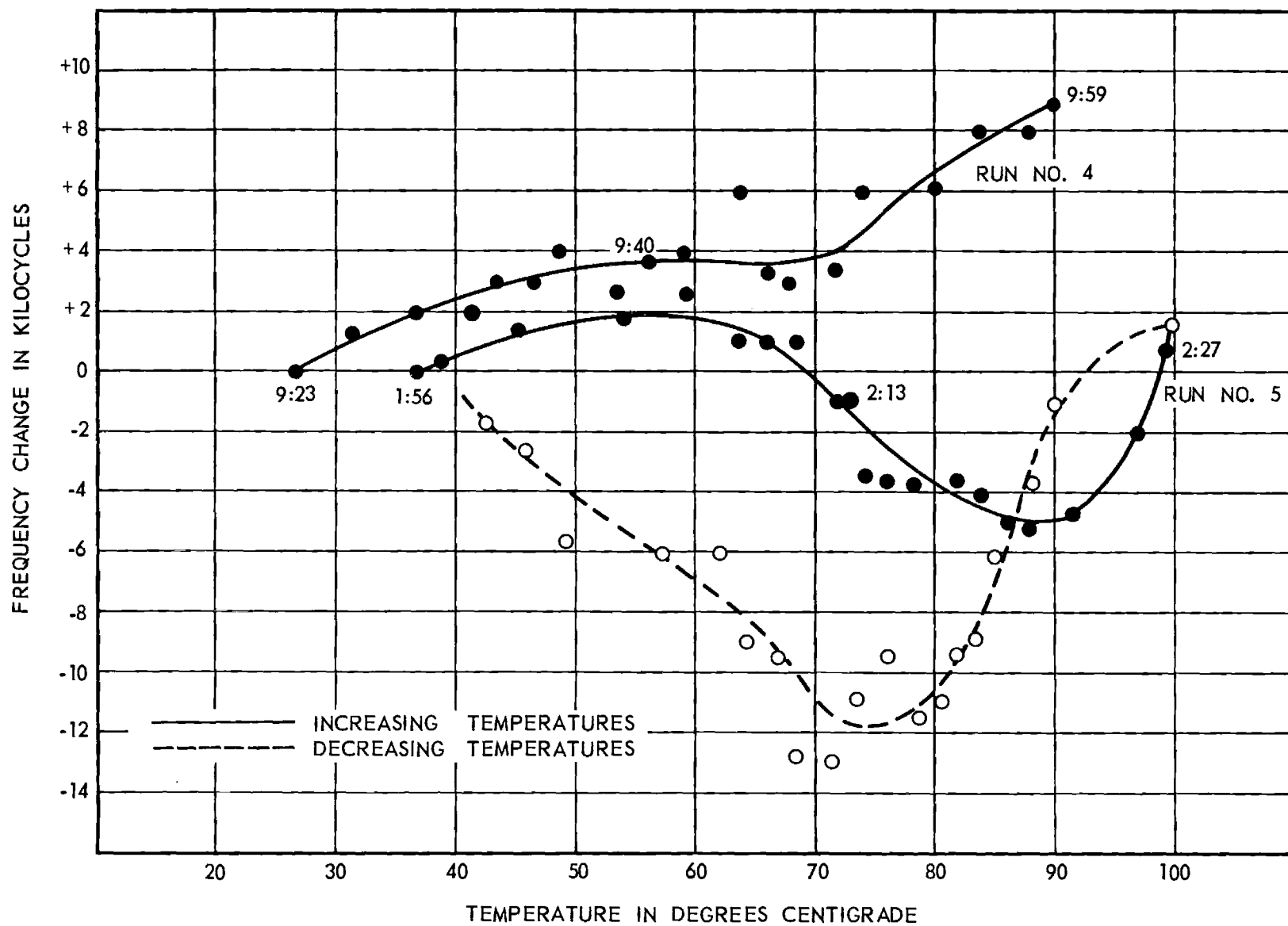


Figure 4.4. Frequency-Temperature Characteristic of a Compensated Brass Cavity (Part One).



Frequency-Temperature Characteristic of a Compensated Brass Cavity (Part Two).

shelf to be left untouched for several weeks. Approximately six weeks after the conclusion of the above tests, one further run was made to ascertain possible deleterious effects due to storage.

This test indicated that the temperature-compensating properties had not been adversely affected. In a temperature run involving one hour to bring the cavity temperature from 27° to 100° C, a total frequency deviation of 10 kc resulted. The maximum frequency deviation was also 10 kc. The average instability was 0.47 ppm/°C.

The Q of this cavity was found in the later tests to be somewhat lower than in the earlier tests. Investigation showed the presence of an air leak which had resulted in loss of dry nitrogen and consequent gain of moist air after temperature cycling. This was not considered significant to the general problem since permanent hermetic sealing can be achieved.

A modified type of resonator in which the mass-to-area ratios are substantially constant is illustrated in Figure 4.6. This cavity has several other features which are believed to be superior. The compensating section, which extends from the inner face of insert plug A to the point of contact of the center conductor on insert plug B, may be varied in length by adjusting the latter's position. Some correction for experimentally determined errors in compensation may thus be effected. A change in resonant frequency occurs when the length of the compensating section is changed; hence, some compromise between the desired frequency and the optimum compensation is necessary. Another innovation in this cavity is illustrated by plug A, i.e., electrical sealing is produced by mechanical pressure of the plug against the inner collar of the outer conductor. In the earlier model, this joint was sealed with solder.

Three cavities, as nearly identical as construction permits, were assembled. Tests of these cavities were made, and data were accumulated over a period of several weeks. The results of five test runs conducted on one of these three cavities is shown in Figures 4.7 and 4.8. In each case, a period of about three hours was involved, the upward cycle usually requiring about one hour and the downward cycle about two hours. It will be noted, that frequency deviations are referred to the frequency existing at the beginning of the run and not to an established or standard frequency of the cavity.

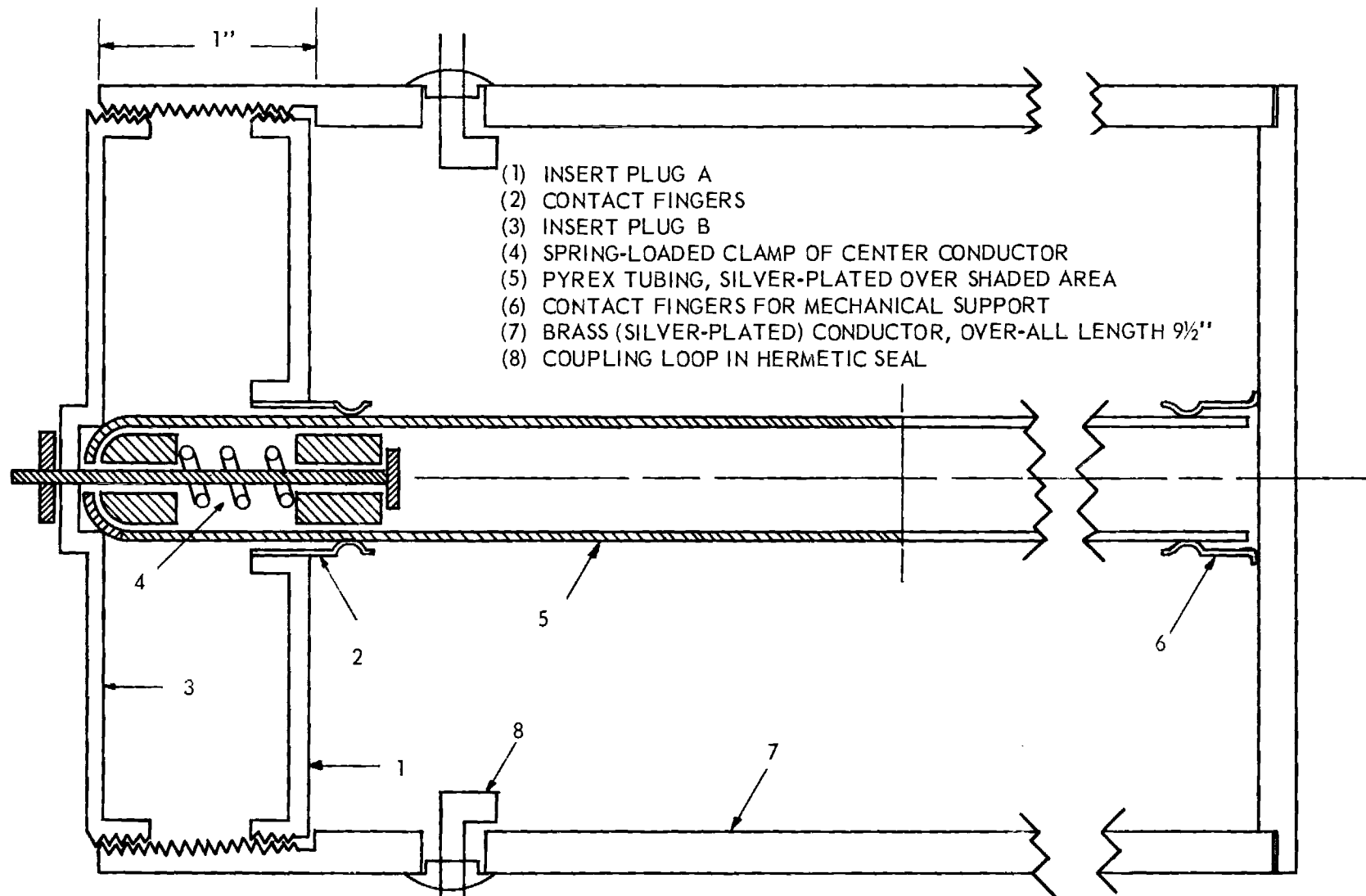


Figure 4.6. Temperature-Compensated Brass Resonator.

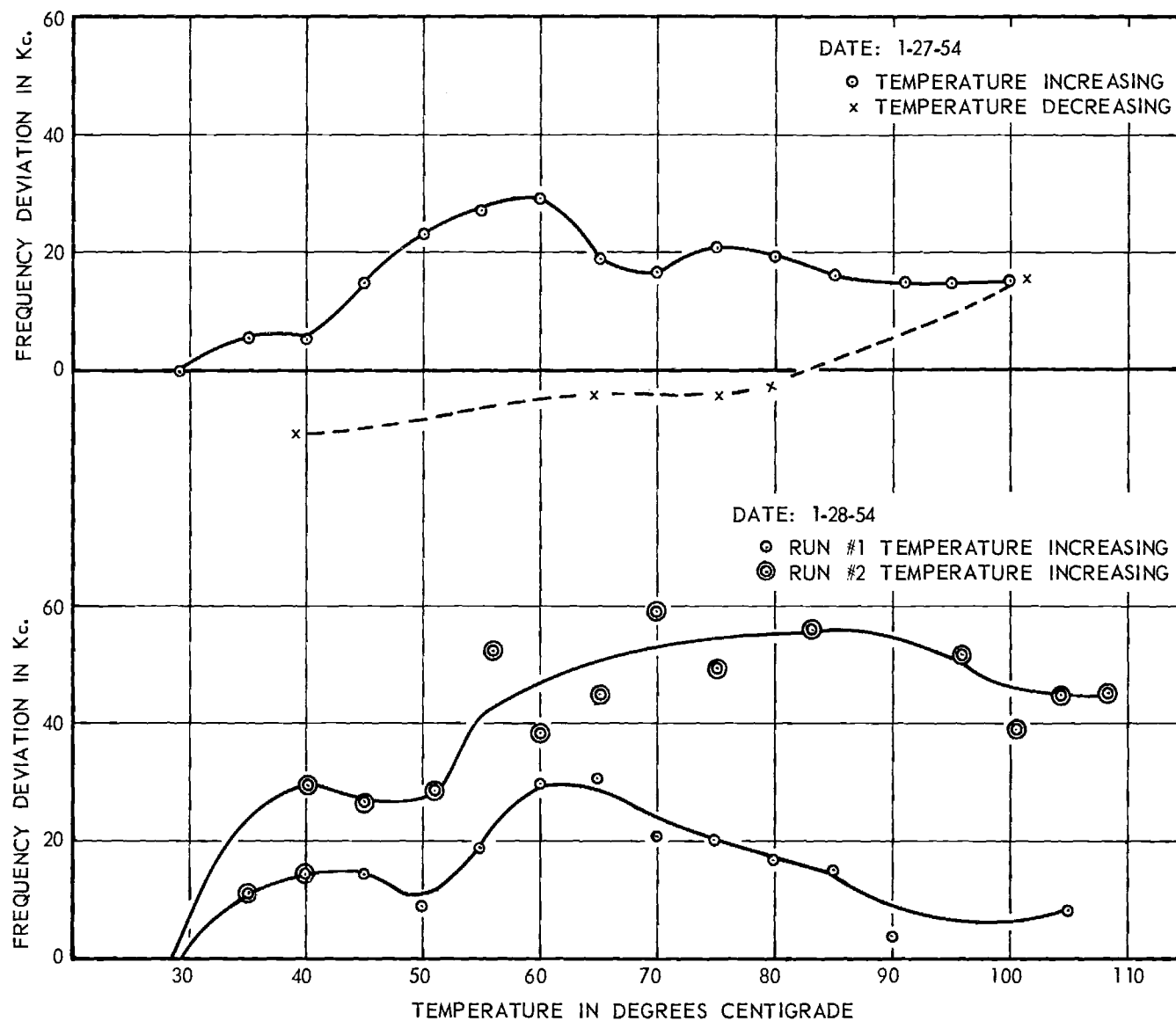


Figure 4.7. Frequency-Temperature Characteristic of a Compensated 600-Mc Brass Cavity.

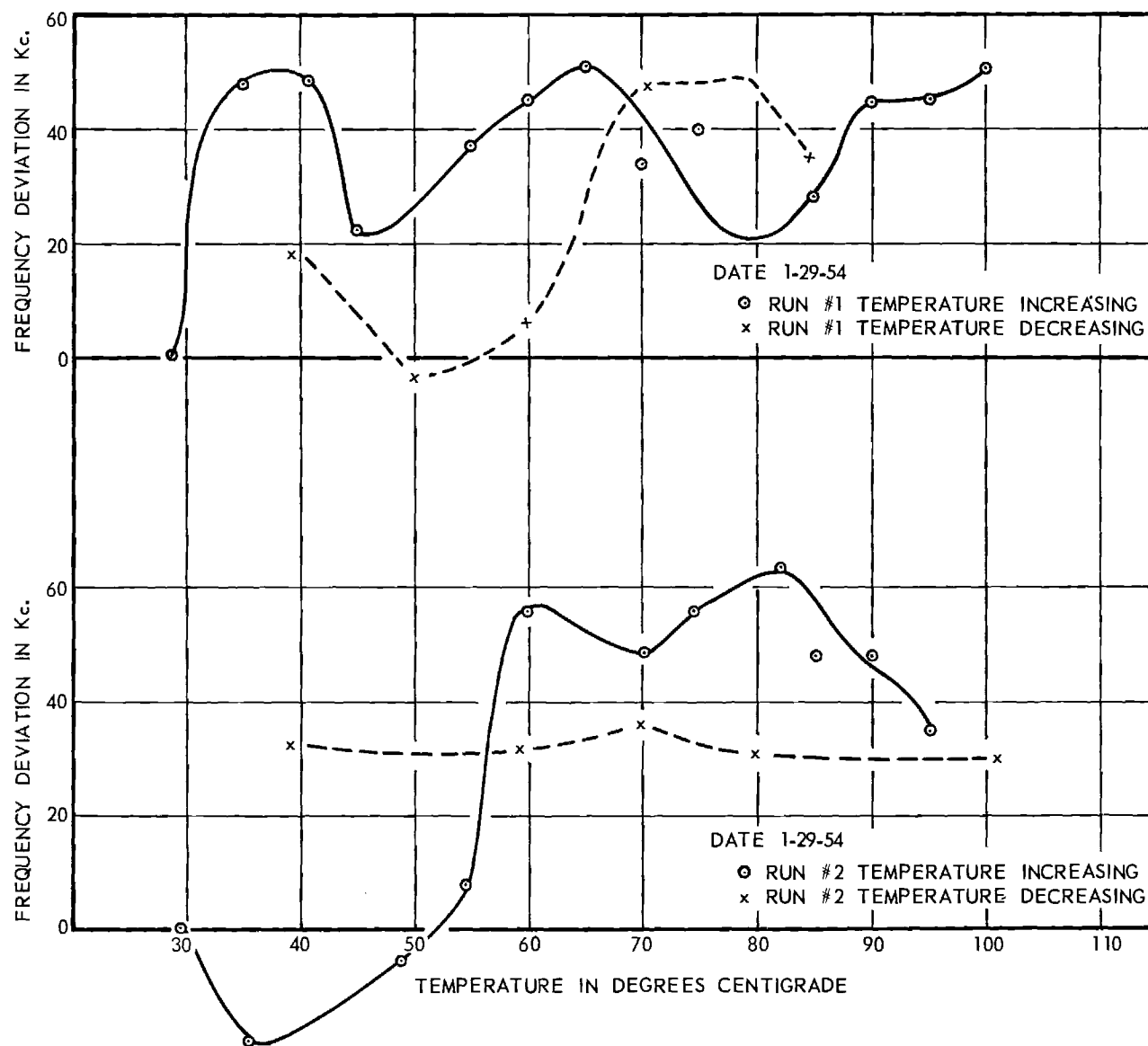


Figure 4.8. Frequency-Temperature Characteristic of a Compensated 600-Mc Brass Cavity.

Inspection of these curves show that the frequency deviation was in most cases considerably less than 1 ppm/°C; since at 600 mc, 1 ppm/°C totaled over 70 degrees is 42 kc.

Although three such cavities were constructed, no tests were conducted on the other two. The planned and actually initiated series of tests on these two was terminated when it was discovered that the Q of each of the resonators was reduced to approximately one-half of the value measured at completion of the assembly. This change occurred within an eight-week period. A further discussion of silvered surfaces is given later in this report along with some plausible reasons for the Q-degradation which was observed.

2. Tunable Compensated Cavities

Those cavities discussed in the preceding paragraphs were designed for single fixed frequencies. The obvious desirability of making the cavity tunable leads to considering means of incorporating such a characteristic without adversely affecting the otherwise desirable properties of the resonator. It has been pointed out that hermetic sealing is required if the resonator is not to be affected by the variable humidity of the atmosphere. A tuning device, then, should be of a type which can be incorporated within, or make connections to, the sealed resonator. With these considerations, a tunable cavity was constructed which maintained a hermetic seal and was not adversely affected by temperature. The construction details are shown in Figure 4.9.

A spring-loaded flexible bellows permits movement of the center conductor under influence of the end cap and at the same time retains hermetic sealing. With the bellows at maximum extension, as illustrated, the resonant frequency of the cavity is at a maximum. If the end cap is screwed into the tubing, the length of the electrically active portion of the center conductor is increased, and the frequency therefore is reduced. The length of the compensating section L should be adjusted to produce optimum compensation in the center frequency to which the cavity must tune.

A tunable cavity of this type may normally be considered as applicable to the relatively narrow frequency band rather than to a broad band. A tuning range of ± 5 per cent is reasonable, a greater range would require greater complexity of methods of controlling mechanical movement.

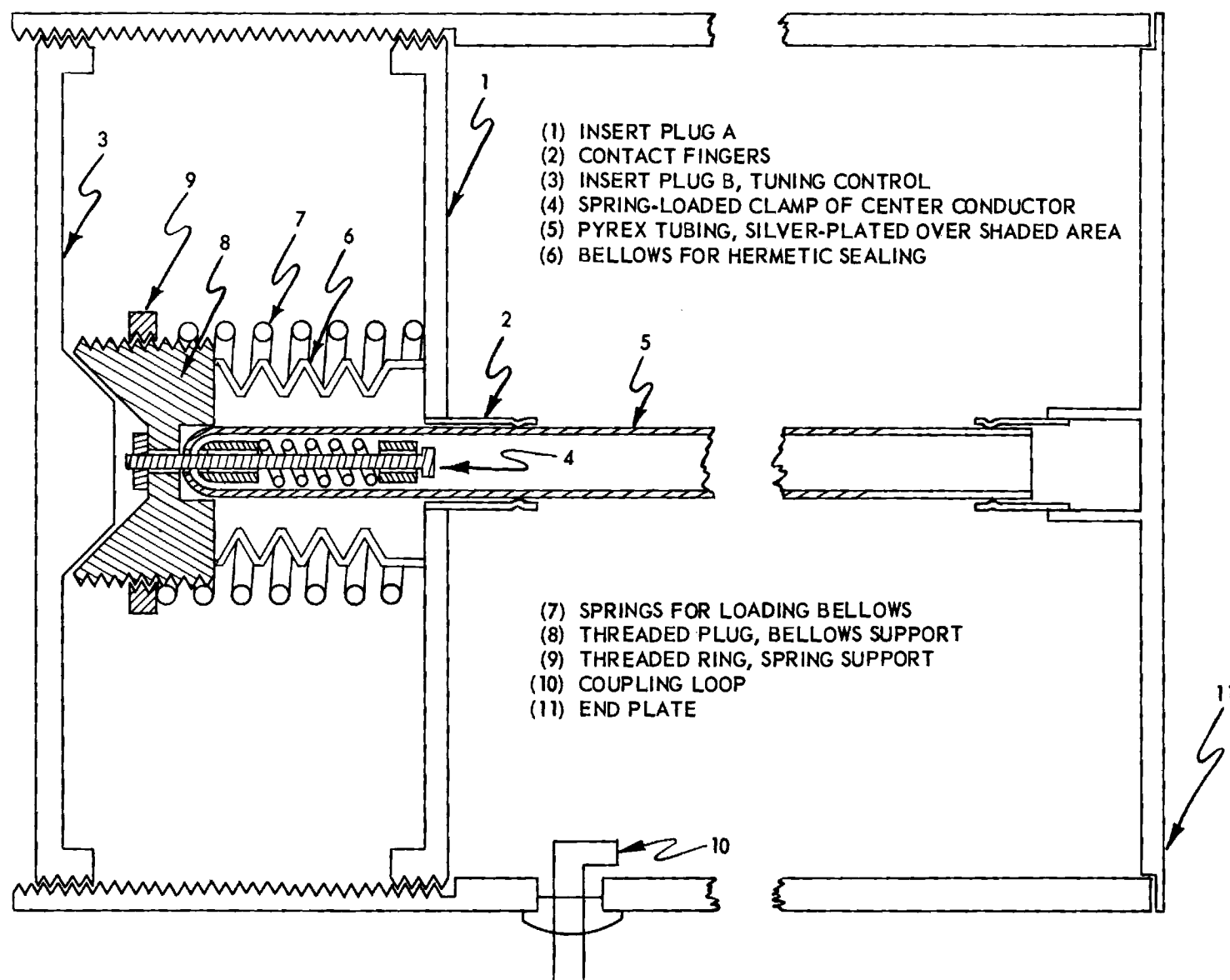


Figure 4.9. Tunable Compensated Cavity.

A limited number of heat-cycling runs have been made to determine the temperature characteristics of the cavity. These are illustrated in Figure 4.10. The curve at the top of the figure illustrates a temperature cycle produced by heated air flowing over the cavity and raising the temperature in the space around the cavity from 29° to 100° C in the elapsed time between 12:12 and 12:53. These and other representative ones are shown on the figure.

It will be noted that a sharp frequency-response lag occurs in the vicinity of the 50-degree point of the curve. This could be caused by a thermal delay within the heavy-walled brass cavity, a phenomenon that has been noted before when cavities have been subjected to rapid heating. No comparable action was observed in the other two runs illustrated. In these, a much slower rate of heating was adopted.

In the upper curve, a maximum frequency deviation of about 55 kc can be observed. In the lower two curves, for which the cavity was tuned to a slightly different frequency, the frequency deviation was in most cases so small that it would be hardly measurable, and a temperature sensitivity of approximately zero was observed.

3. Compensated Non-Tunable Cavity with Invar Center Conductor

The same general configuration used for compensation of Pyrex center conductors has been applied. This is illustrated in Figure 4.11. It will be noted that the Invar rod is secured firmly to the end plate by a machine screw inserted in the end of the rod. This method differs from that employed with Pyrex. In the latter arrangement, the Pyrex tubing was held with moderate firmness by a spring-loaded screw and derived its principal rigidity from the support of spring fingers at each end of the cavity proper.

The compensating section (which is exaggerated in length in this sketch) is represented by the spacing between the two plugs at the right. In this case, this spacing should be approximately 1/20 of the length of the electrically active part of the center conductor since Invar has a coefficient of expansivity of approximately unity and brass a corresponding coefficient of about 20.

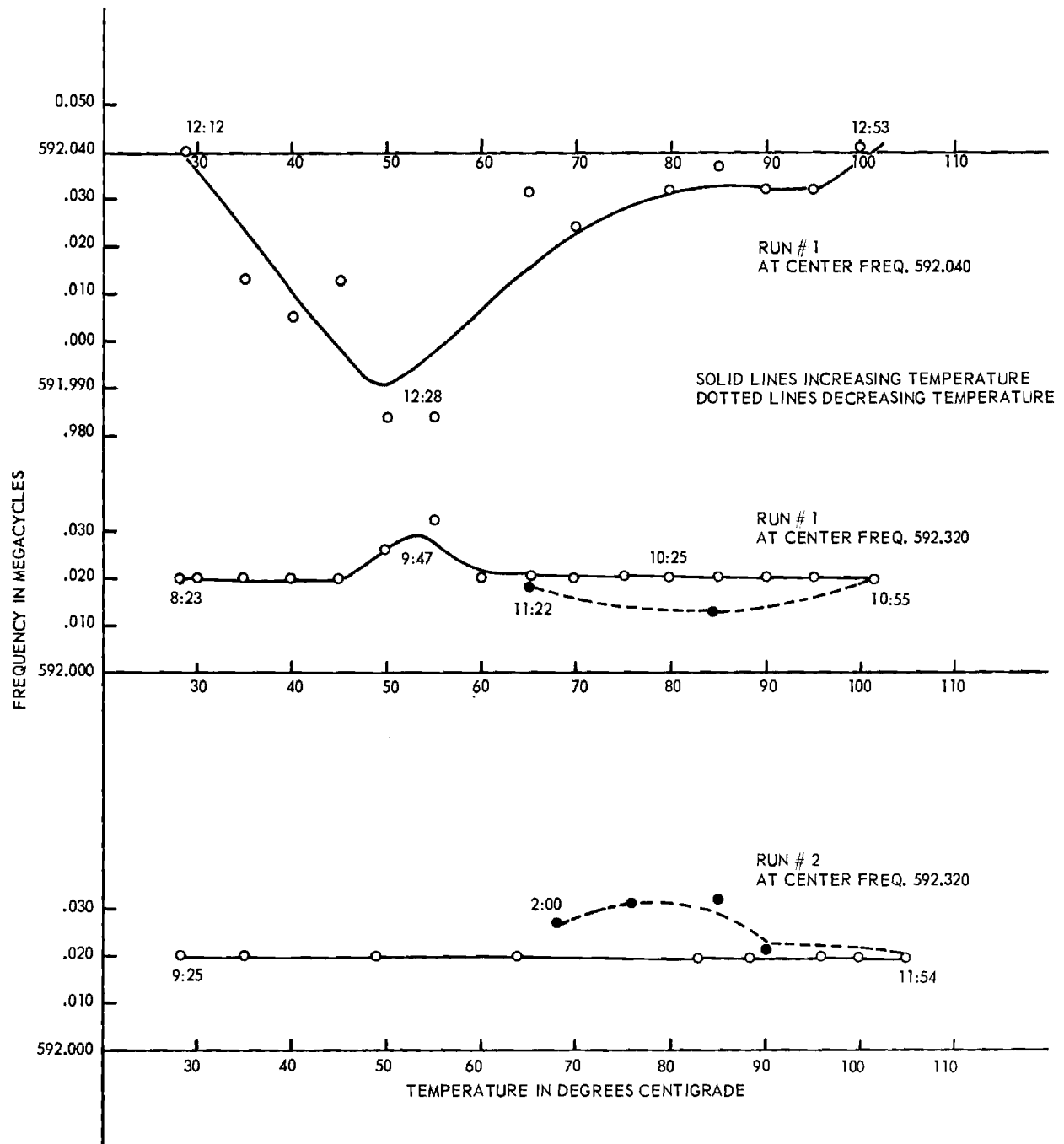


Figure 4.10. Temperature Characteristics of Tunable Compensated Brass Cavity.

A number of temperature runs have been made with this cavity. The results have been inconsistent, but in no case has the theoretical temperature insensitivity of the combination been attained. The unsatisfactory results may have been due to flexural stresses transferred to the inner conductor via the rigid mounting previously mentioned. These stresses may be expected to be unpredictable both in magnitude and in direction. An improvement in temperature characteristics might be effected by adoption of a spring-loaded type of mounting to avoid these stresses and strains.

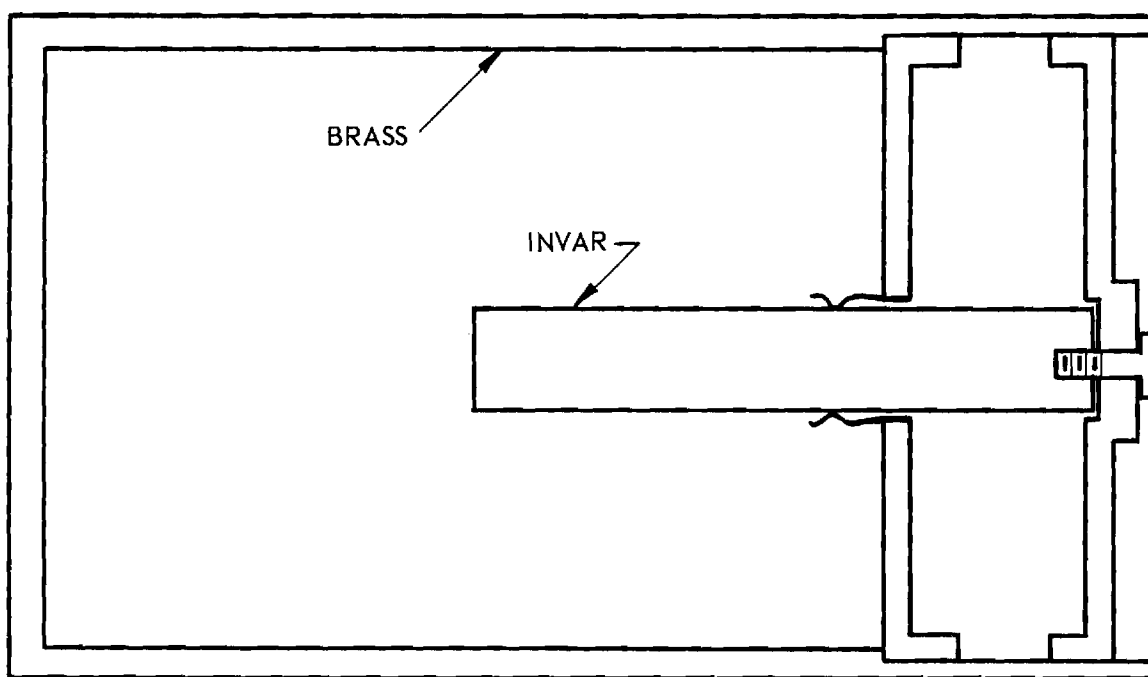


Figure 4.11. Compensated Cavity with Invar Center Conductor.

4. Cavities of Low-Expansivity Materials (Uncompensated)

It is evident that the complexity of construction existing in the compensated cavity is unwarranted provided equivalent characteristics can be achieved by simpler means. The attractive characteristics of certain low-expansion materials indicate that it should be possible to utilize these in the desired temperature-insensitive resonator. However, problems of fabrication may overbalance the advantages otherwise gained. For example, the ceramic Stupalith has a

claimed zero temperature coefficient. However, it failed to retain a silvered surface upon exposure to soldering temperatures and, as a result, first appeared unsatisfactory for use. Techniques which lead to the successful plating and soldering of this completely temperature-insensitive material were developed in the course of this contract.

Early tests with uncompensated cavities failed to realize a temperature insensitivity equal to that determined by the coefficient of expansivity of the center conductor. It was theorized that stresses and strains introduced into the center conductor may have produced added errors to account for the discrepancies in temperature sensitivity. In an attempt to establish a method of mounting wherein no rigid contact exists between the inner and outer conductors, the configuration in Figure 4.12 was adopted. In this arrangement, the free end of the center conductor is held firmly, but not rigidly, by spring fingers. The other end, which is electrically active, is soldered to another set of spring-finger contacts.

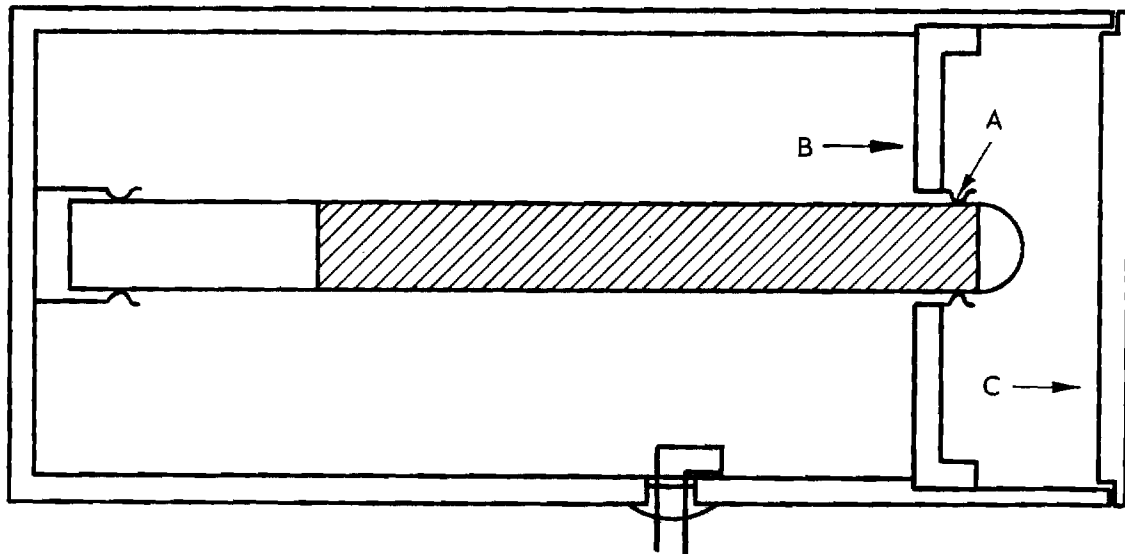


Figure 4.12. Arrangement of Parts of Uncompensated Cavity with Vycor Center Conductor.

The electrically active portion of the conductor is located between the soldered tips A and the end of the cross-hatched section at the left. The plug B is threaded and may be forced tightly against the shoulders as illustrated in order to effect a satisfactory electrical bond. The plug C is used to hermetically seal the cavity.

The results of several frequency-versus-temperature runs are illustrated in Figure 4.13. Several temperature-cycling runs preceded these recorded here. During these earlier runs, considerable erratic frequency variations occurred, but these anomalies became less pronounced with subsequent cycles. It appears that some further erratic behavior may account for the abrupt dip between 30 and 50 degrees in curve No. 1.

If only runs 2 and 3 are taken into account, it is found that the maximum frequency variation was approximately 40 kc. The average deviation in run 2 represents less than $1/2$ ppm/ $^{\circ}$ C while that of run 3 is slightly greater. These results indicate that a cavity of this type is satisfactory for applications where moderate orders of stability are satisfactory. However, present data indicate that compensated cavities must be utilized if higher orders of stability are required.

5. Effects of Temperature on an Invar Cavity

Invar is a nickel-steel alloy which has been extensively used for cavity resonators. A 36 per cent nickel content produces an alloy which has minimum expansivity (about 1 ppm/ $^{\circ}$ C). Although the compensated cavity utilizing an Invar center conductor did not produce anticipated results, it was assumed that an uncompensated cavity of Invar could be made to give substantially anticipated results if the inner conductor could be screwed into the end plate by means of threads accurately machined on the inner conductor proper.

An oscillator had been built and tested using this construction. As will be fully described in a later section herein, the temperature instability measured was very nearly equal to that which was theoretically assumed. The purpose of this test was to measure temperature gradients at various points in the cavity as the ambient temperature was varied.

The Invar cavity was fitted with thermocouples at the points indicated in Figure 4.14 and was immersed in an oven. The temperature was gradually raised for a period of over an hour while readings from each of the thermocouples were taken. The curves shown in Figure 4.15 indicate the rising ambient temperature. The lower temperature inside of the cavity is due to the thermal lag in the cavity material. The lag of temperature at the "outer" position is approximately

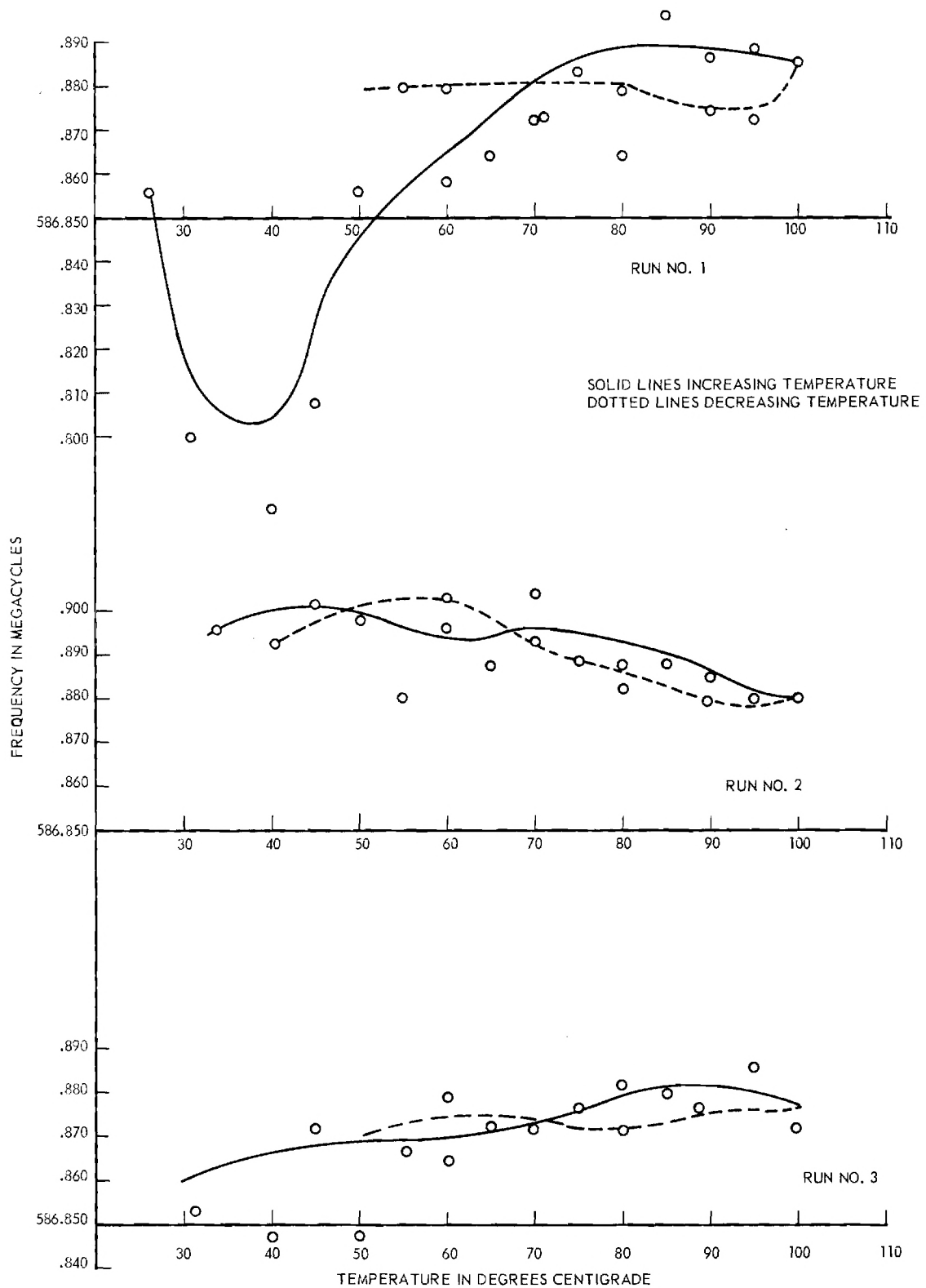


Figure 4.13. Temperature Characteristics of Uncompensated Cavity with Vycor Center Conductor.

20 minutes behind that of the ambient temperature for this particular rate of rise. It must be assumed that the temperature at the "outer" position would have an appreciable effect on the frequency of oscillation since this is at the top end of the inner conductor. Also of considerable interest is the temperature of the "inner" position, which is also on the inner conductor but at its base. This part of the cavity is seen to be at a higher temperature than the "outer" position but still lags the "wall" and "outside" positions, a result of the heat-conduction lag.

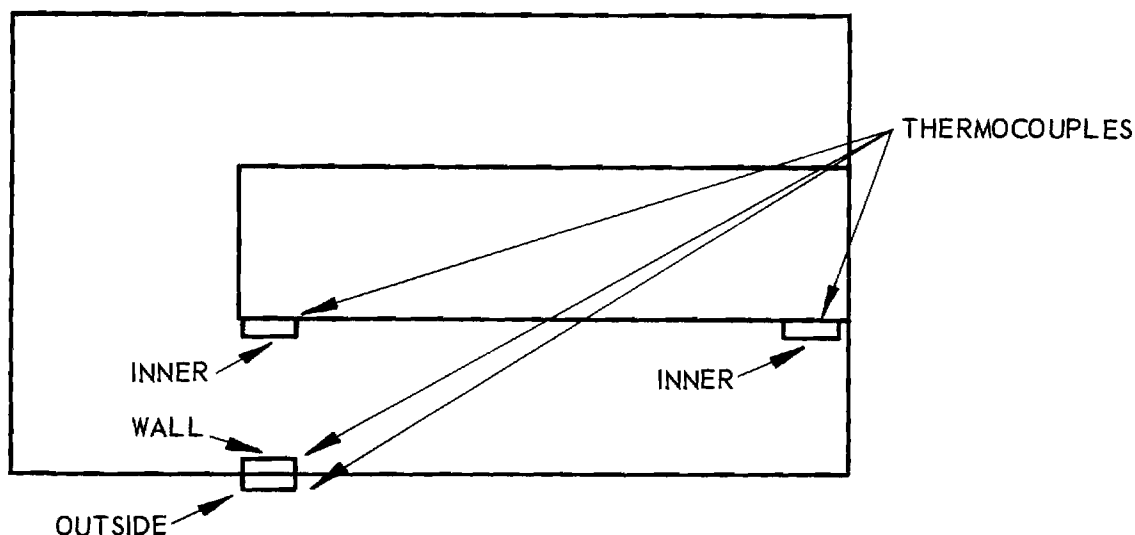


Figure 4.14. Thermocouple Positions in Invar Cavity.

Another type of heat run was taken with the thermocouples in the same positions. This time the cavity was left at ambient temperature, and a 6AF4 vacuum tube was placed inside in the same manner as though the entire configuration was truly an oscillator. Plate and filament voltages were supplied to provide approximately the same power dissipation as would be expected in the oscillator, although no attempt was made to make this configuration oscillate.

The temperature-versus-time data are plotted in Figure 4.16 for this test. After the temperatures had almost reached a condition of equilibrium, the oven was energized and its temperature slowly increased. During the first 75 minutes, the "outer" position rose to an equilibrium condition of about 30° C higher than ambient temperature, while the "wall" and "inner" position increased 11° and 12° C, respectively. The "outside" was only 7° C higher.

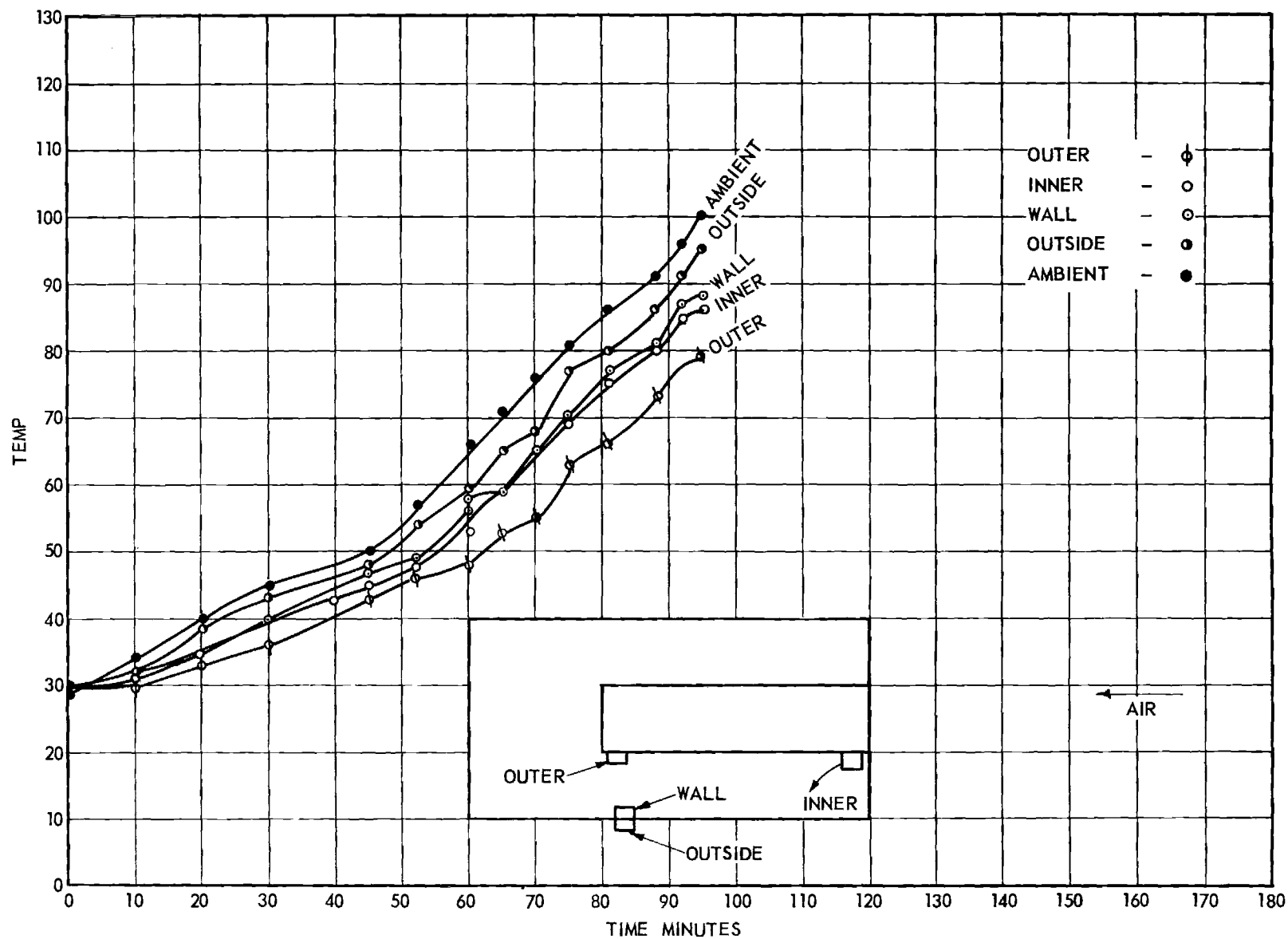


Figure 4.15. Effect of Ambient Temperature on Invar Cavity.

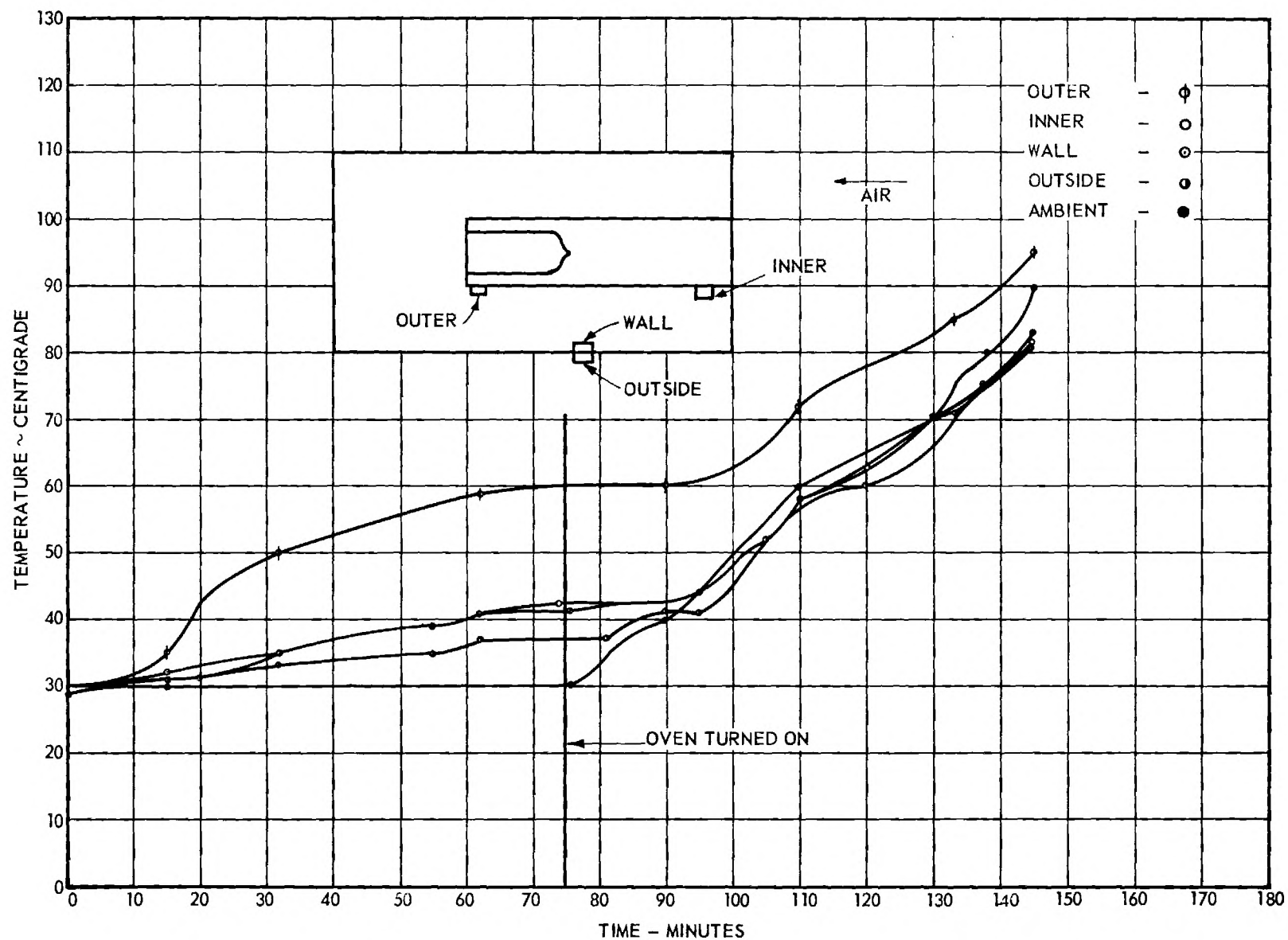


Figure 4.16. Effect of Ambient Temperature and Internal Heat on Invar Cavity.

If one assumes that the frequency is determined entirely by the length of the inner conductor, thus neglecting "end" effects, it would be necessary to integrate the temperature gradient of the inner conductor to determine the incremental length increase. An average temperature rise would be $\frac{30 + 11}{2} = 20.5$ degrees. This represents a frequency change of approximately 20.5 ppm, and this amount of change was, in fact, measured in the Invar cavity oscillator during the first five minutes after it was turned on.

The oven was turned on after 75 minutes of operation, the change-over point being shown on the curve. The most significant conclusion reached here seems to be that the temperature of the inner conductor changed negligibly during the next 15 minutes even though the ambient temperature rose 10° C during this time. The "outside" temperature did show a rise, however.

The apparent thermal lag due to the low heat conductivity of Invar makes it ideally suited for use as a cavity material, since rapid ambient-temperature variations about a mean value have very little effect on the actual temperature of the cavity. Furthermore, the complementary characteristic of low expansivity permits little change in cavity dimensions.

6. Invar Cavity with Stupalith Center Conductor

A later section in this report describes the difficulties in plating ceramic materials with a good conductive surface. Techniques were finally developed which produced a successful adhering surface that can be soldered with a special non-contracting solder. After these techniques were developed, an Invar cavity was constructed which utilized Stupalith as a center conductor. Since the Stupalith has a claimed zero expansivity, no change in length of the center conductor was anticipated, and, hence, this cavity should be virtually insensitive to temperature variations. The construction of this cavity is shown in Figure 4.17. The center frequency of this cavity was about 812 mc. It was subjected to several temperature-cycling runs in which the temperature was raised in 10-degree steps and held at each step for a period of one hour. Results obtained from these tests indicated a frequency change in the order of 2 ppm/°C--a figure which is higher than the expansivities of either the Invar or the Stupalith.

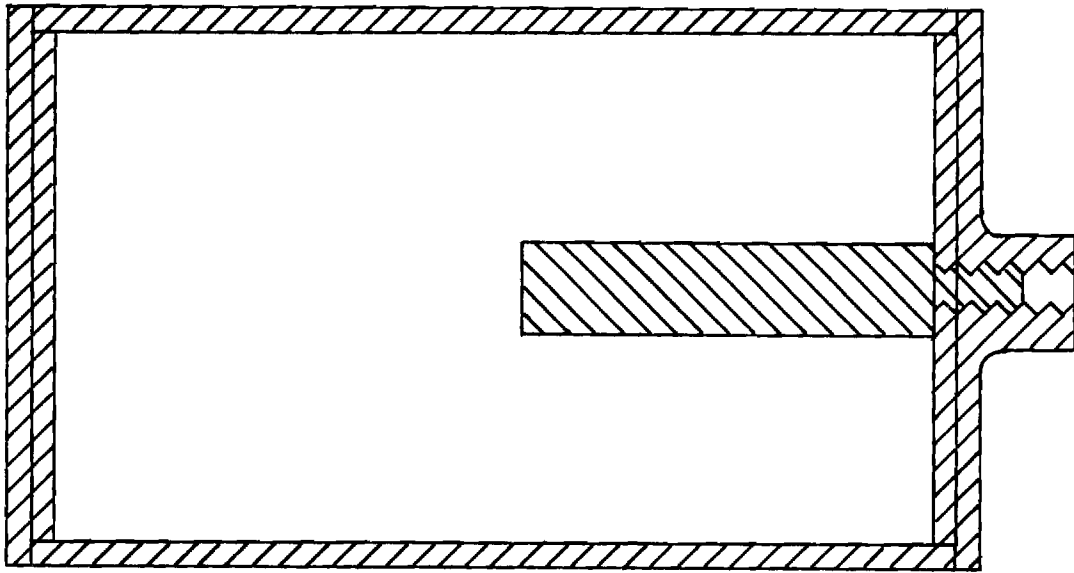


Figure 4.17. Invar Cavity with Stupalith Center Conductor.

This resultant high-temperature sensitivity may be the result of stresses in the end plate transferred to the center conductor, or it may possibly be due to the silver or solder entering under the butt joint at the base of the Stupalith rod. Time did not permit pursuing an investigation of this type of cavity any further under the present contract, but work will be resumed at the completion of this report.

V. CAVITY-CONTROLLED OSCILLATORS

A. Introduction

The preceding chapter described methods of constructing high-Q, temperature-insensitive cavities but did not discuss methods by which these cavities might be employed in frequency control. This chapter is concerned with various factors involved in combining vacuum tubes and coaxial cavities into an oscillatory system. Two obvious combinations include that in which the tube is exterior to the cavity and that in which the tube is interior to the cavity. When the tube is exterior to the cavity, the method of coupling between the two is usually done by means of inductive loops inserted at a low-impedance point in the cavity. The impedance, or admittance, presented to the tube at the loop terminals is a primary determining factor of oscillator performance.

The first part of this chapter presents an analysis of the input admittance of a loop-coupled cavity. The remaining portions describe a number of cavity-controlled oscillators and their characteristics.

B. Input Admittance of a Loop-Coupled Cavity

The analysis of the input admittance of a cavity must include the physical coupling link, whatever its configuration. Inasmuch as inductive coupling by a closed loop is widely used, the succeeding discussion applied to such a configuration. The results may, however, be applied to any type of coupling wherein the coupling link exhibits an admittance comparable to that of the closed inductive loop. For a complete analysis of the parameters introduced by various types of coupling, the reader is referred to Beringer (4). The analysis is started by assuming that the loop-coupled cavity may be represented as shown in Figure 5.1. In this figure, L_2 , C_2 , and R_2 represent the equivalent inductance, capacitance, and losses of the cavity, while L_1 and R_1 represent the inductance and losses of the coupling loop. A number of useful parameters are introduced and defined in Table 5.1.

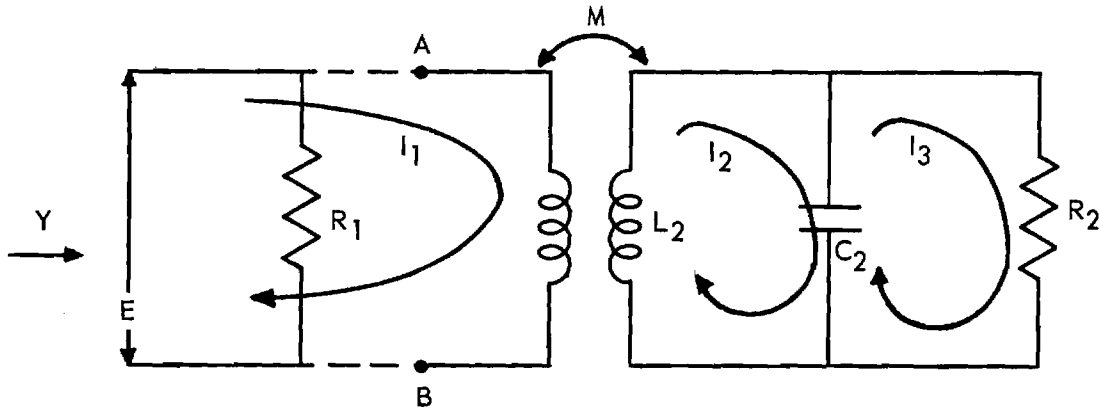


Figure 5.1. Equivalent Form of Loop-Coupled Cavity.

TABLE 5.1

NOTATION

$K = M / \sqrt{L_1 L_2}$	Coupling coefficient
$\omega_2 = 1 / \sqrt{L_2 C_2}$	Resonant frequency of secondary
$Q_1 = R_1 / \omega_2 L_1$	Primary Q
$Q_2 = R_2 / \omega_2 L_2$	Secondary Q
$m = 1 - k^2$	Useful dimensionless factor
$Y = G + jB$	Input admittance
$\phi = \tan^{-1} B/G$	Phase angle of admittance
$k_c = \text{critical } k$	
$X = \omega / \omega_2$	

The input admittance of terminals A and B may be determined by a straightforward application of Kirchhoff's Laws. From the first law

$$\begin{aligned}
 I_1 (j\omega L_1) - I_2 (j\omega M) &= E \\
 - I_1 (j\omega M) + I_2 \left(j\omega L_2 + \frac{1}{j\omega C_2} \right) - I_3 \left(\frac{1}{j\omega C_2} \right) &= 0 \\
 - I_1 (j\omega C_2) + I_3 \left(R_2 + \frac{1}{j\omega C_2} \right) &= 0.
 \end{aligned} \tag{5.1}$$

If this equation is solved for I_1 , and the quotient E/I_1 is taken, there results

$$Y_{AB} = \frac{1 + j (\omega R_2 C_2 - R_2 / \omega L_2)}{\omega L_1 \left[\frac{\omega M^2 R_2 C_2}{L_1 L_2} - \omega R_2 C_2 + \frac{R_2}{\omega L_2} + j \left(1 - \frac{M^2}{L_1 L_2} \right) \right]} \quad (5.2)$$

Considerable simplification may be obtained by introducing several definitions from Table 5.1. Equation 5.2 then becomes

$$Y_{AB} = \frac{1 + jQ_2 \left(x - \frac{1}{x} \right)}{\omega_2 L_1 [Q_2 (1 - x_m^2) + jxm]} \quad (5.3)$$

The effect of the losses in the loop may be taken into account by the addition of $1/R_1$ to this expression. It is now helpful in the analysis to convert the equations to a dimensionless (normalized) form by multiplying both sides of equation 5.3, with the loss term added, by $\omega_2 L_1$ to obtain

$$Y\omega_2 L_1 = \frac{1 + jQ_2 \left(x - \frac{1}{x} \right)}{Q_2 (1 - x_m^2) + jxm} + \frac{1}{Q_1} \quad (5.4)$$

Careful consideration was given to various means of interpreting this final equation. It was finally decided to substitute numerical values of Q_1 and Q_2 , values which would be representative of the resonances now under study. A value of 100 was selected for Q_1 and 1000 for Q_2 . This latter number is somewhat lower than may be expected from a coaxial cavity, even if heavily loaded, but an appraisal of equation 5.4 shows that variation of Q_2 is reflected almost directly as an equivalent scale factor. Therefore, curves of admittance plotted against the frequency variable may be easily applied to other values of Q_2 .

Figures 5.2, 5.3, and 5.4 represent the various component parts of the input admittance, susceptance, conductance, and phase angle in the case of $Q_1 = 100$ and

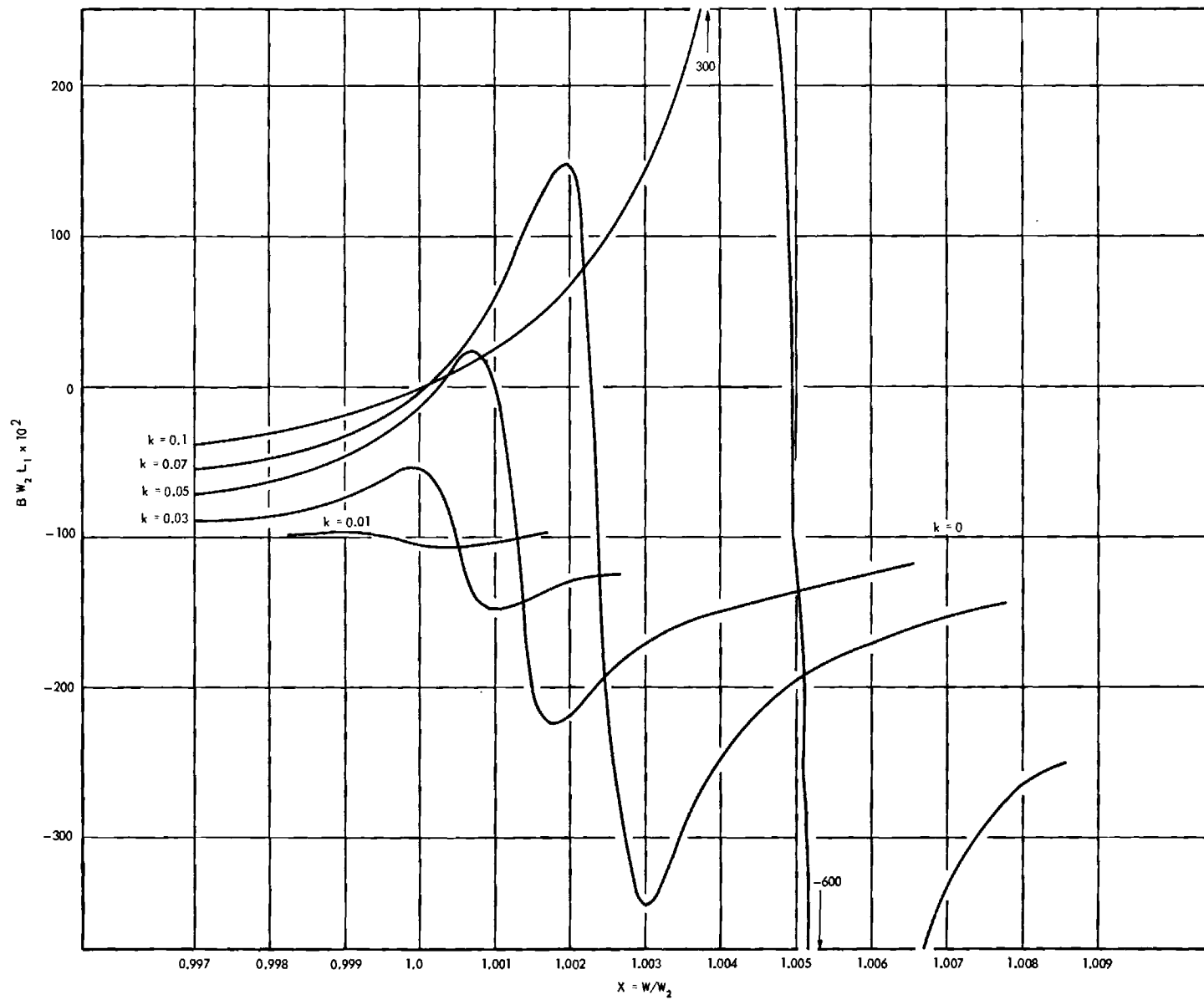


Figure 5.2. Input Susceptance of a Loop-Coupled Cavity.

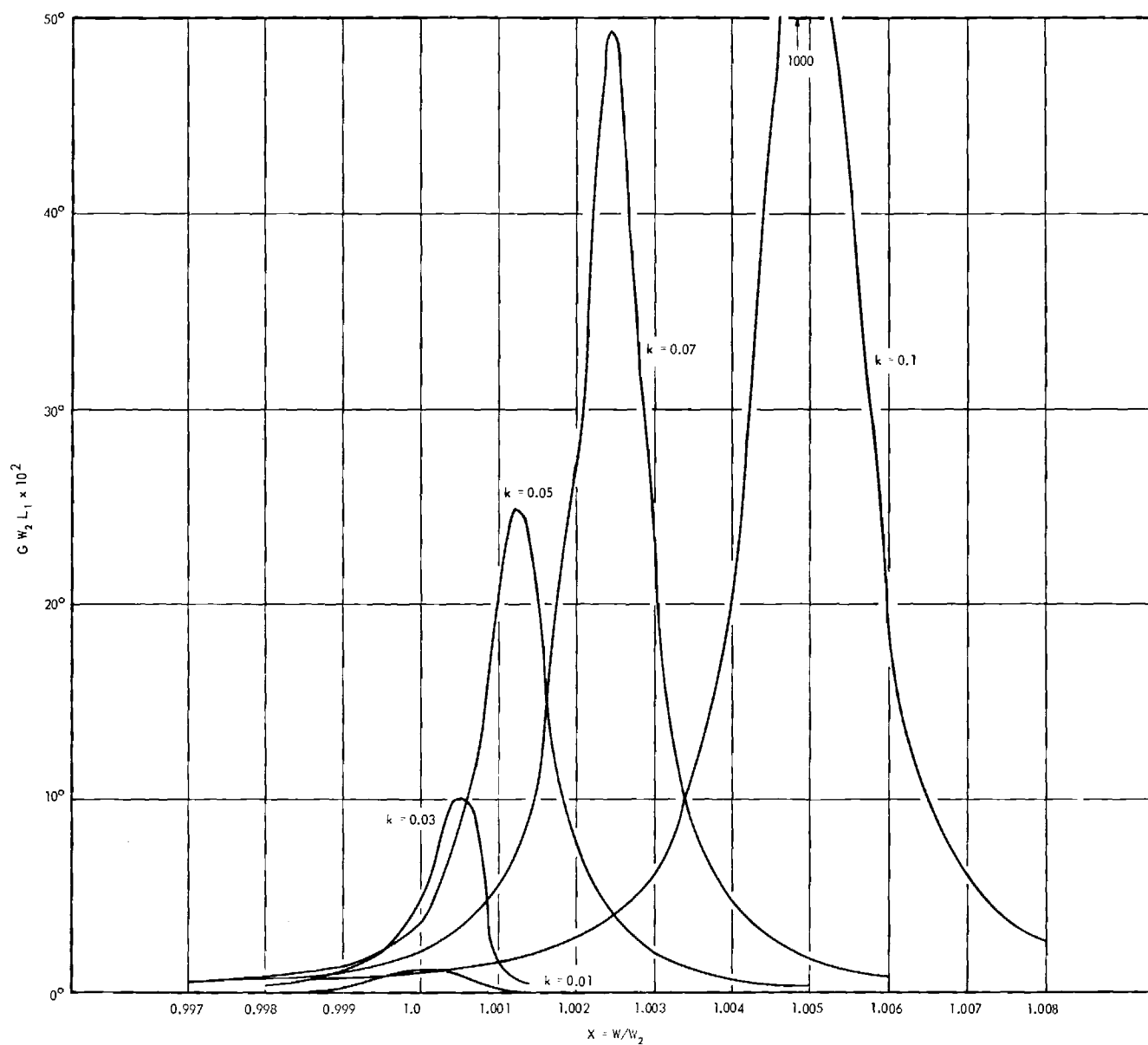


Figure 5.3. Input Conductance of a Loop-Coupled Cavity.

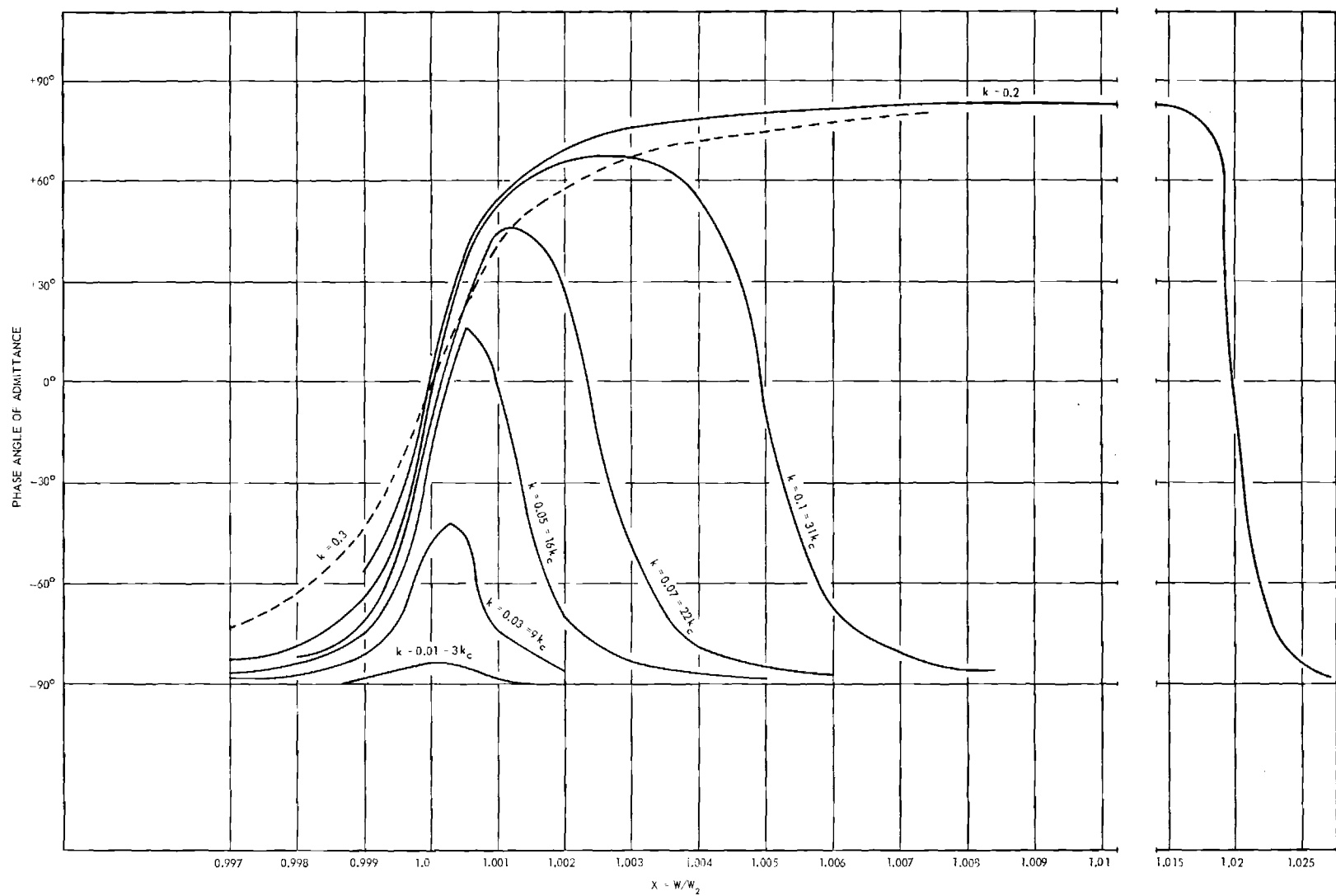


Figure 5.4. Phase Angle of Input Admittance.

$Q_2 = 1000$. The parameter selected is the coefficient of coupling k ; it in turn is represented both numerically and in terms of the critical coefficient of coupling k_c .

The information displayed in these figures provides a further tool in the design of a cavity-controlled oscillator. If the data presented here are combined with formulas for evaluating coupling and cavity characteristics, the actual admittance at the input terminals may be computed with some accuracy.

C. Methods of Coupling an Oscillator to a Cavity

The analysis of the previous section leads to values of admittance at the actual input to the cavity. In practice, it may be difficult to place the pins of the oscillator's vacuum tube at the true input point. A 500-mc cavity-controlled oscillator which was constructed apparently did achieve this pin position when the tube base was mounted in the end wall of the cavity. At this position, values of input admittance of the cavity, as measured on an r-f bridge, compared favorably with values computed by methods of the previous section. It was not difficult to achieve cavity control of oscillation, and the oscillator, when under cavity control, exhibited good stability.

At frequencies exceeding 500 mc, the effects of leakage inductance introduced by connecting leads from the oscillator to the cavity loop became appreciable. When this leakage inductance becomes appreciable in magnitude as compared to that inductance which is coupled from the cavity, the stability of the oscillator is reduced since the Q of the leakage inductance is much lower than the Q of the cavity. For this reason, oscillators of the type pictured in Figure 5.5 were discarded in favor of other methods which will be described subsequently. It should be pointed out, however, that this arrangement gave exceptionally fine orders of stability for oscillations below 500 mc. Since this investigation pointed toward frequencies above 500 mc, no attempt was made to further exploit this arrangement.

In order to avoid effects of leakage inductance due to lead lengths, the possibility of mounting the tube inside the cavity was investigated. If this internal mounting could be employed, then the flux produced by any wire in the tube configuration would also link the conductors of the cavity and vice-versa. In this way, the leakage inductance should be reduced since all of the flux produced is confined within the cavity walls.

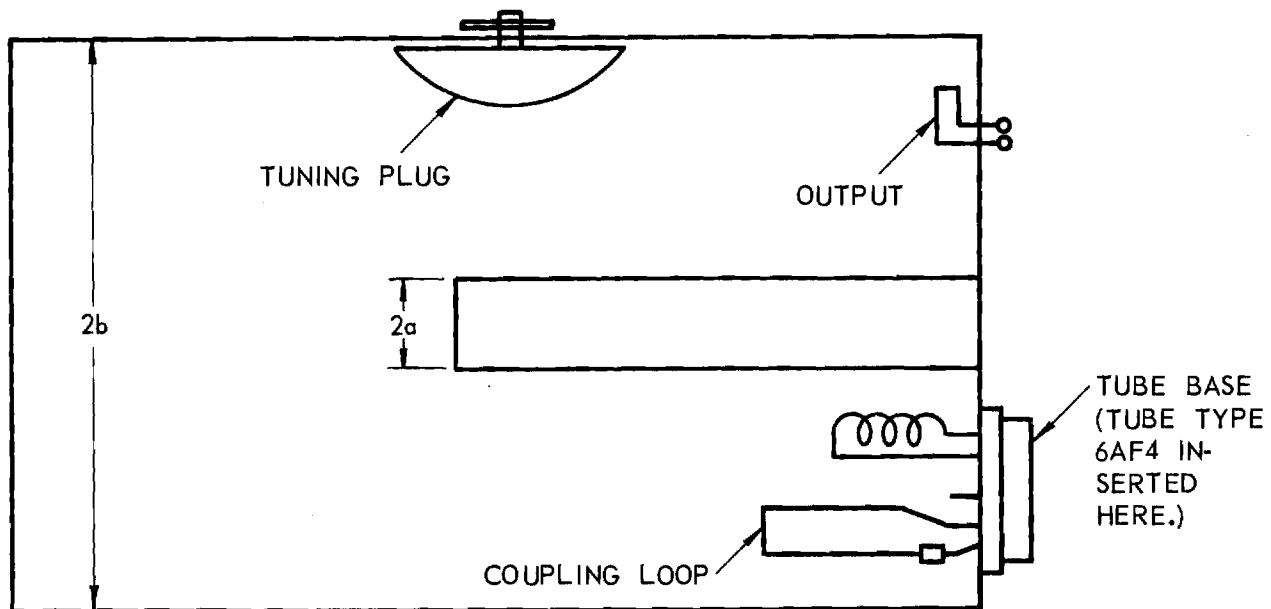


Figure 5.5. Loop-Coupled Oscillator and Cavity.

The first arrangement tested was a type of conductive coupling in which the tube was placed between the inner and the outer conductors of the cavity at a point of low impedance. A schematic diagram of this configuration is shown in Figure 5.6. A parallel line resonator is shown for the purpose of simplicity. The impedance between grid and plate is a maximum at the open end where, neglecting losses, it equals $jZ_0 \tan \frac{2\pi l}{\lambda}$. At all other points it is the parallel combination of Z_1 and Z_2 . The impedance of this combination becomes very small as x becomes small, and the oscillator should cease to run because of insufficient plate to grid impedance. The test was begun by placing the tube at the open end and progressively moving it toward the shorted end while readings of frequency and instability of frequency due to anode changes were taken. As the tube was moved closer to the shorted end, the frequency rose while the instability decreased. This process was continued with the anticipation that a point of minimum instability could be reached. This point could not be reached, however, because at a point near the base, the frequency jumped discontinuously to a value of almost twice the resonant frequency with a corresponding increase in instability of more than tenfold. The anomaly was observed

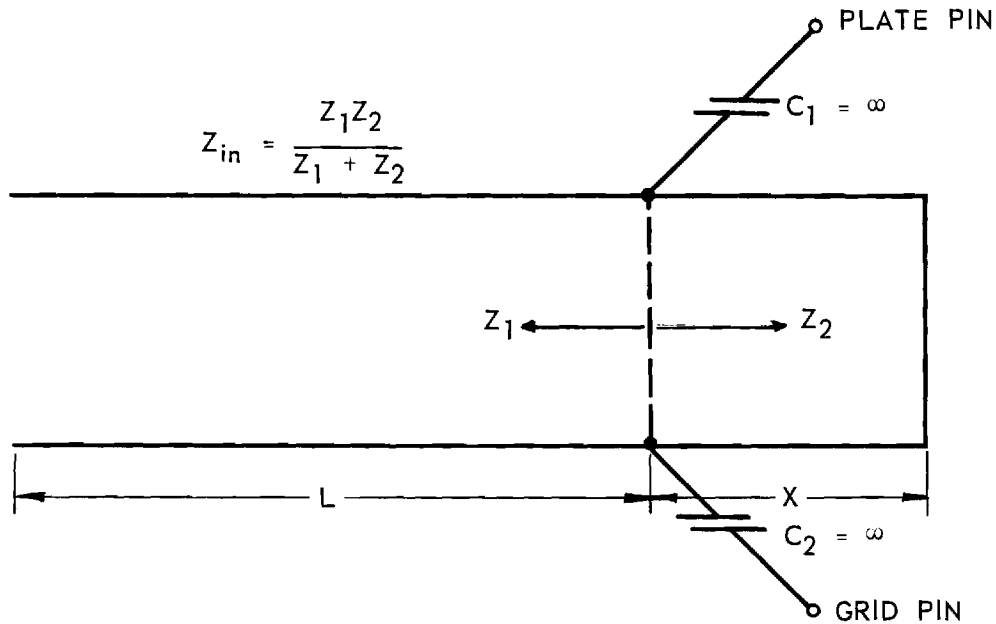


Figure 5.6. Conductive Coupling to Cavity.

in both parallel lines as well as coaxial cavities and could be repeated consistently. No feasible explanation of this effect has been advanced at this time, and because the stability was not considered good at any point, no further effort was made to investigate the possibilities of this arrangement other than to note its simplicity of design and construction.

A configuration has been devised which attempts to maintain the advantage of conductive coupling at the open end of the cavity and at the same time to minimize the disadvantages. The circuit arrangement is essentially that of the Clapp oscillator, in which a small capacitor is placed in series with the plate-to-grid inductance. The effect is to reduce the effective inductance of the frequency-determining element without materially affecting its Q.

In the UHF version of this oscillator, the plate-to-grid inductance is represented by the cavity. If the series-capacitor is made very small, corresponding to a high capacitive reactance, the cavity will operate close to its natural resonant frequency. Thus, the effect of the series capacitor is to "isolate" the reactance of the vacuum tube from the cavity. Since the capacitor

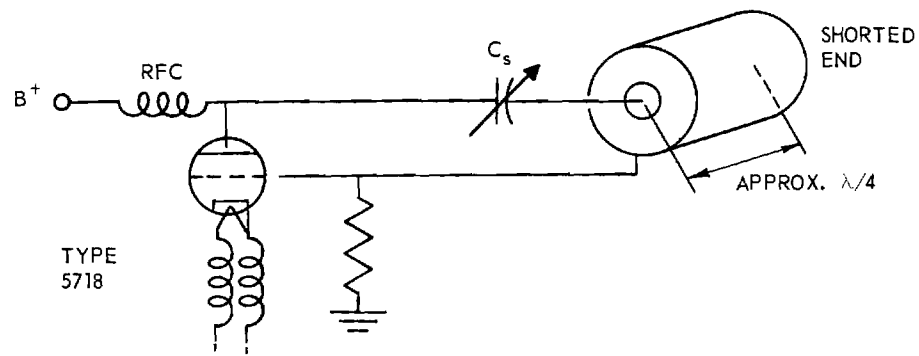
is in series with the resonator and the tube, the tube is essentially connected to a low-impedance point because of the series-resonant combination. The limiting factor in the reduction in size of the series capacitor is the amount of inductance that can be obtained from the cavity. It has been shown that the maximum inductance obtainable is a function of the Q of the cavity. As the series capacitor is reduced, the inductive reactance must be increased by the cavity. This is accomplished by an increase in frequency. When a condition is reached where more inductive reactance is needed than can be supplied, the result is cessation of oscillations.

The basic circuit of the oscillator along with a physical arrangement and the equivalent circuit are illustrated in Figure 5.7.

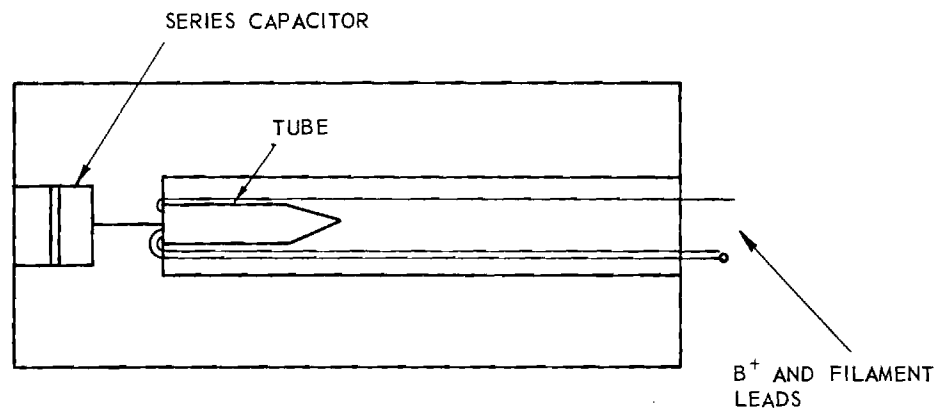
In Figure 5.7 B, the vacuum tube is mounted in the center conductor of the cavity. This arrangement has been used with several types of tubes including subminiature type 5718, the 6AF4, and pencil triodes. The adaptability of this configuration to hermetic sealing is readily seen.

An attempt to optimize the parameters available must be made if this circuit is to be used for precision frequency control. The largest size cavity consistent with space requirements is usually selected, but its dimensions must be small enough so that the propagation of higher modes is impossible. In a cavity of fixed outer diameter, a diameter ratio of outer-to-inner conductors of 3.6 will result in a cavity of optimum Q . Another important aspect is that the oscillator in Figure 5.7 B will operate at a frequency lower than the resonant frequency of the cavity and at a point on the reactance slope which is determined by the characteristic impedance. The following qualitative discussion is presented to afford an insight into the problem of optimizing the diameter ratio of conductors.

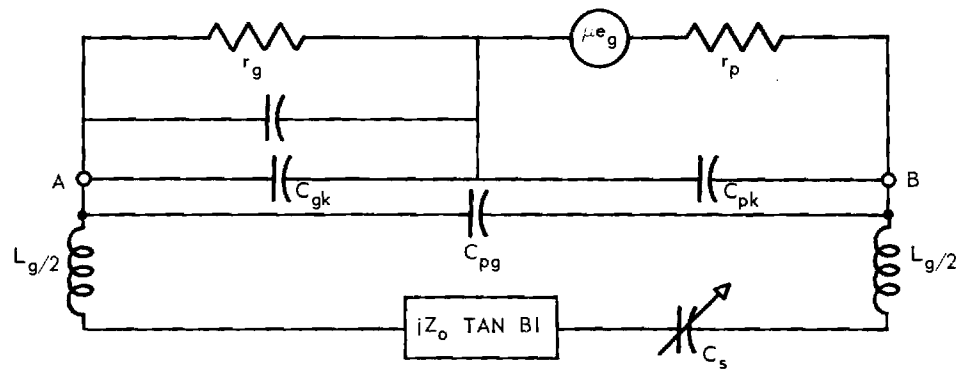
It has been pointed out that the coaxial cavity must offer an inductive reactance of sufficient magnitude to overcome the series-capacitor reactance. The magnitude of inductive reactance furnished by the cavity at any given frequency is directly related to its characteristic impedance. If the two pertinent reactances of the complete oscillator, i.e., the cavity reactance and the negative of the tube reactance, are plotted against frequency, they will intersect



A. OSCILLATOR SCHEMATIC



B. CIRCUIT MOUNTING



C. EQUIVALENT CIRCUIT OF OSCILLATOR

Figure 5.7. Physical and Electrical Arrangement of Series-Capacitor Oscillator.

at an angle having a magnitude dependent upon their respective slopes. A measure of oscillator stability is found by assuming a shift in the tube-reactance curve. The two intersections projected upon the frequency axis indicate the frequency shift which may be expected to occur.

These relationships are illustrated in Figure 5.8, which represents the reactance $\text{Im } [Z(j\omega)]$ of two cavities having different characteristic impedances, Z_1 and Z_2 , but having the same resonant frequency. The sums of the reactance of each cavity and of series capacitors are illustrated by dotted lines. An optimum theoretical frequency stability should result from a cavity-reactance curve which exhibits a vertical slope at the point of intersection with the tube line and that this condition could be approached by lowering the characteristic impedance of the cavity and/or increasing the series capacitive reactance. Continuous lowering of the cavity impedance may not increase the vertical slope, however, since the Q of the cavity is decreased at the same time. There must exist, then, an optimum characteristic impedance, not necessarily that corresponding to optimum Q , which will give optimum stability.

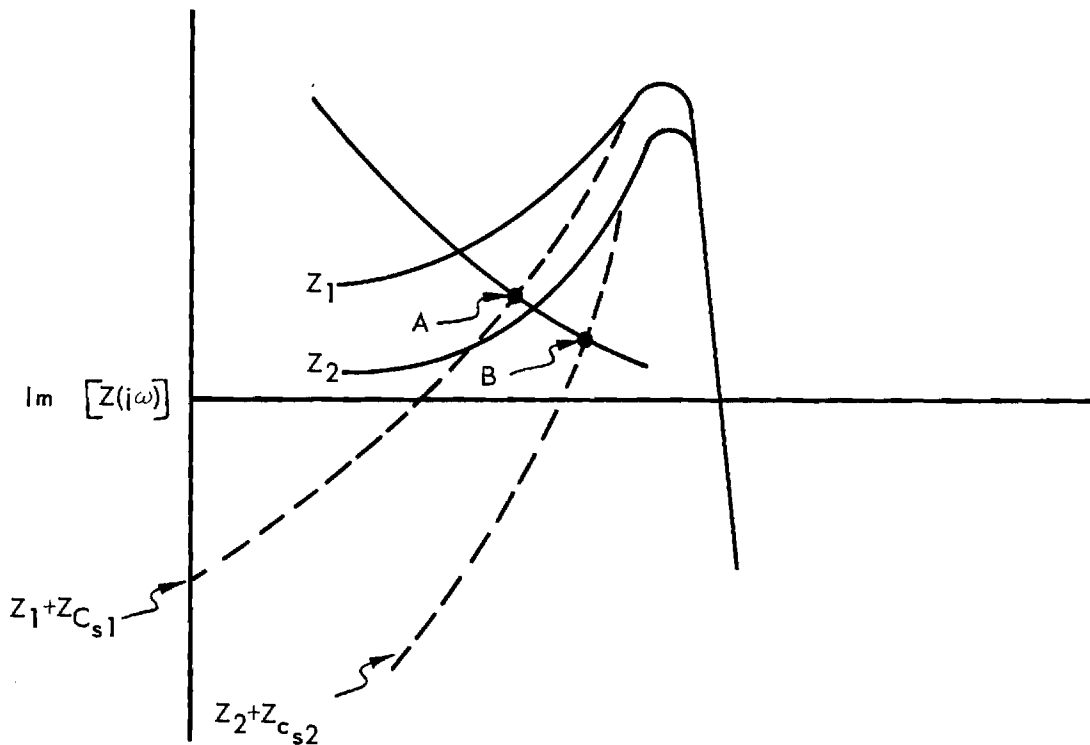


Figure 5.8. Effect of Varying the Cavity Characteristic Impedance.

Efforts to analyze this problem analytically met with diverse results. It was decided that experimental methods should be used in an attempt to find the optimum parameter. Actually, experimental results would be used to check any analytical result if at all possible.

In order to provide convenient vehicles for attaining several different values of characteristic impedance and Q_1 , outer conductors of two different diameters and five inner conductors of widely varying diameters were constructed. Figure 5.9 shows these five conductors (with end plates). The value of characteristic impedance for each is shown directly above its respective center conductor. The relative sizes of inner and outer conductors may be visualized by comparing the center conductor to the end plate.

The series capacitor, seen in Figure 5.7 B, was selected to provide both a relatively small magnitude of capacity and a wide tuning range. Two different models of capacitors have been utilized. One, designated as the High Ratio Concentric Air Capacitor, manufactured by the Johanson Manufacturing Company is illustrated in a photograph of a completed oscillator and is shown in Figure 5.10.

This capacitor permits a variation of approximately 1 to 33 μmf . The other model utilized is designated as a JFD VC-5 or VC-11 manufactured by the JFD Manufacturing Company. The latter types are tubular in design and are composed of low-expansivity materials compensated in such a way that an over-all expansivity of zero is specified.

The photographs in Figures 5.10 and 5.11 illustrate an oscillator which has demonstrated better orders of stability than have been attained with similar configurations. Using conductor B (of Figure 5.9), the oscillator is made to operate over the frequency range of approximately 400 to 550 mc. Three curves in Figure 5.12 illustrate certain of its characteristics. The lower curve shows the instability in parts per million per volt change in anode potential (ppm/v) when the anode potential was increased from 100 to 150 volts. The center curve depicts the frequency drift of five and ten minutes, respectively, after setting the oscillator to a new frequency, while the upper figure illustrates the frequency drift when the oscillator is operated from a cold start. It is interesting

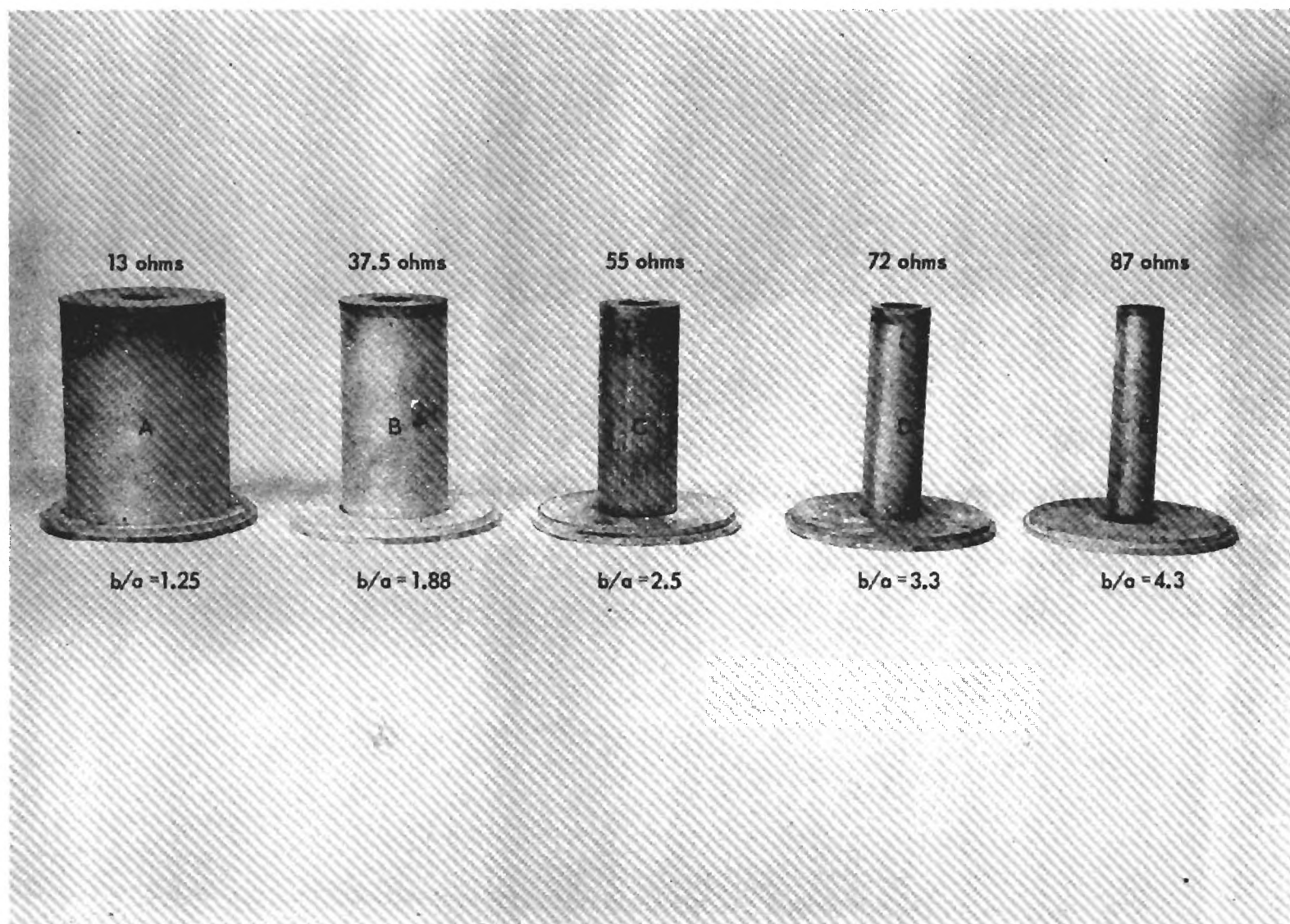


Figure 5.9. Photograph of Series of Center Conductors for Coaxial Cavity.



Figure 5.10. Cavity-Controlled Oscillator, Opened to Show Tube Base and Series Capacitor.

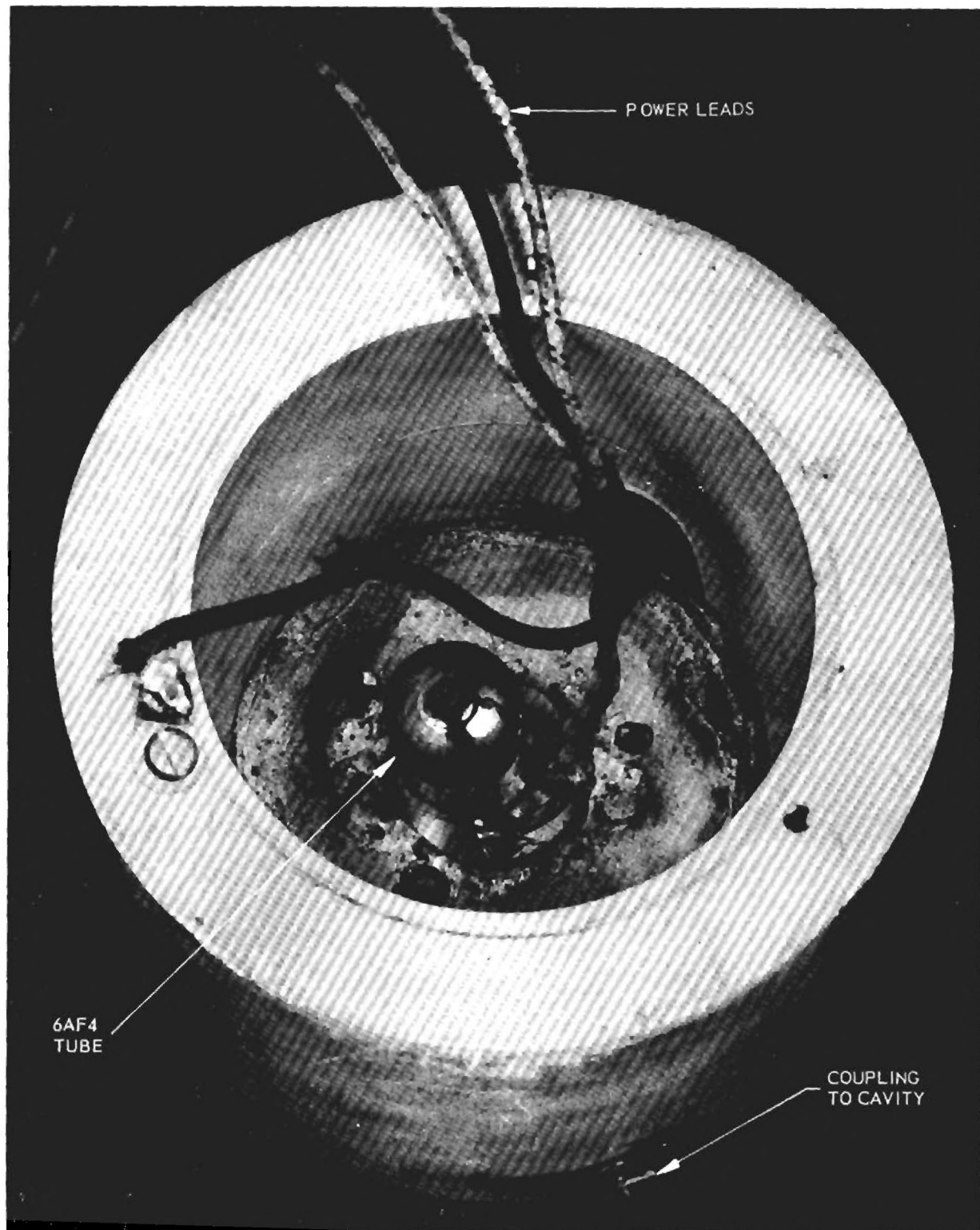


Figure 5.11. Cavity-Controlled Oscillator, Showing Method of Mounting Tube.

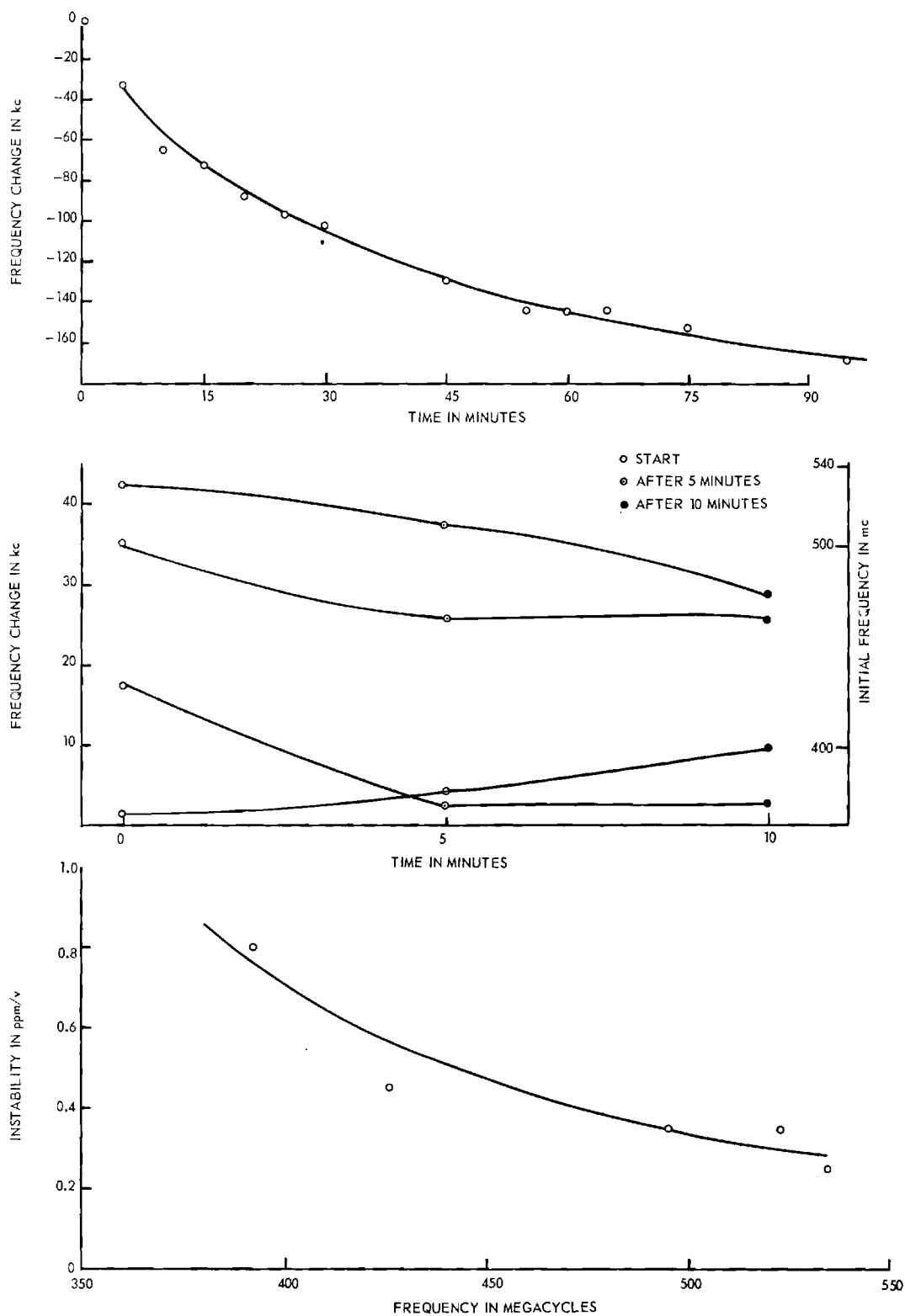


Figure 5.12. Characteristics of Oscillator Shown in Photographs of Figures 5.10 and 5.11.

to note that the known temperature coefficient of brass of about 20 ppm/°C would approximately account for the frequency drift experienced in the case of operation from a cold start.

The investigations of the several resonators formed from the center conductors shown in Figure 5.9 have resulted in data which conform, in part, to the qualitative analysis previously advanced relative to the relationship among characteristic impedance, series capacitive reactance, and stability. The use of a cavity having a lower impedance than that which is required for optimum Q has permitted operation at higher frequencies than is possible with the high Z_0 's. This action is illustrated in Figure 5.13, particularly, and to a lesser extent in Figure 5.14. The first of these figures illustrates the characteristics of an oscillator when the Z_0 of the cavity is varied, all other parameters remaining constant. Cross sections of the cavities concerned are shown in the upper right-hand corner of the figure. The curves of instability show that instabilities of less than 1 ppm/v mark the cavities of lower characteristic impedance, but that instabilities of greater than 10 ppm/v are observed at the lower frequency end of the high- Z_0 cavity.

Figure 5.14 illustrates the characteristics of similar cavities in which the type 6AF4 tube has been replaced by its subminiature counterpart, the 5718. It will be noted that a common trend is observed for each of the cavities. At the high-frequency end, the frequency stability is best; as the frequency is lowered the stability decreases logarithmically.

Figure 5.15 illustrates the stability characteristics of similar oscillators which utilize coaxial cavities with outer conductors of smaller diameters. Although a considerably more attractive physical package results from the use of the small outer conductor, it appears to be necessary to accept decreased stability if the smaller package is utilized. Instabilities no greater than 1 ppm/v have been obtained, as may be observed by reference to Figure 5.15. Since the Q of the cavity is decreased through reduction of cavity dimensions if the ratio of b/a is held constant, the poorer stability when compared with the larger cavities is to be expected.

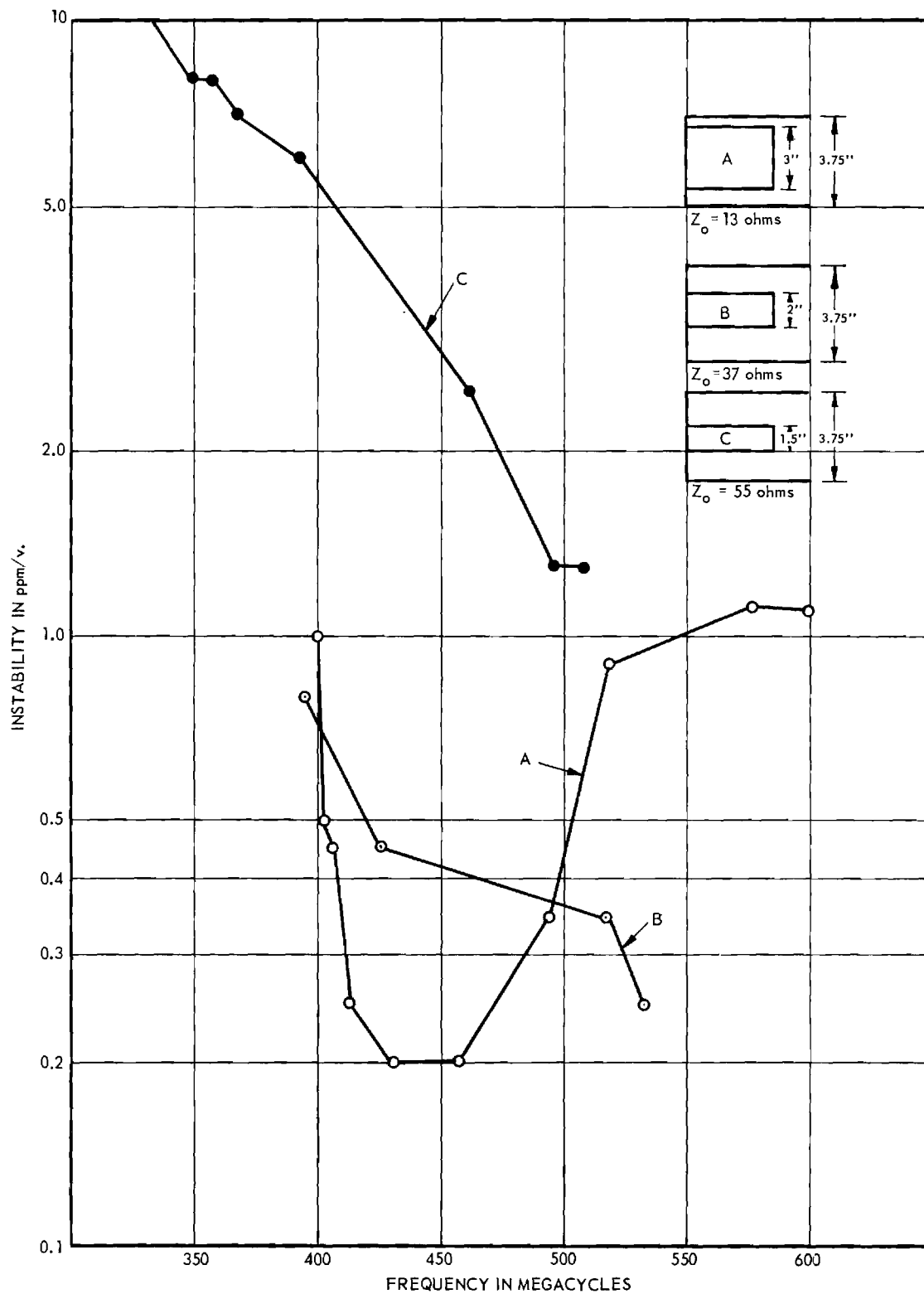


Figure 5.13. Stability Characteristics of Oscillator Controlled By Cavities of Different Z_o 's, Using Tube Type 6AF4.

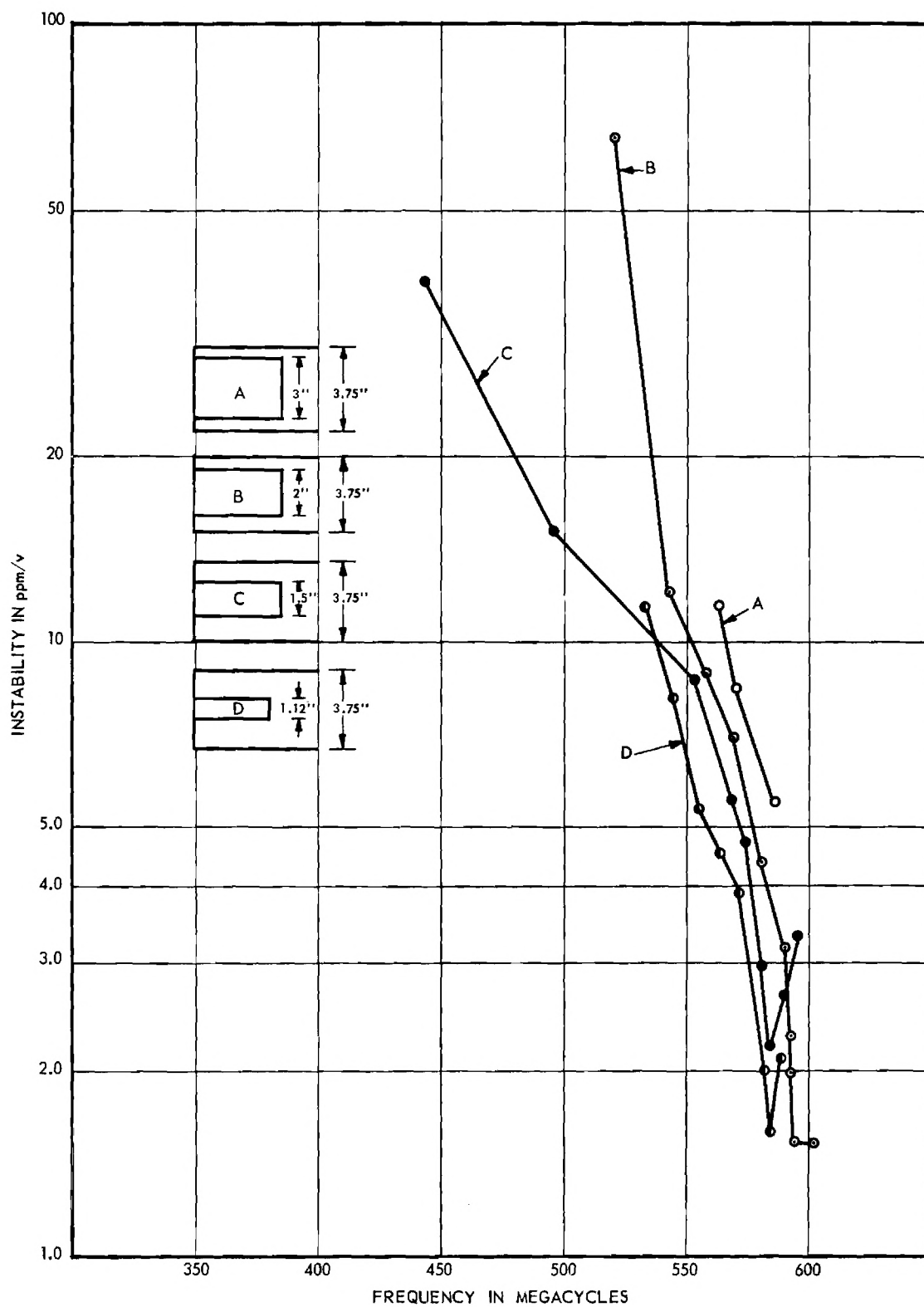


Figure 5.14. Stability Characteristics of Oscillators Controlled by Cavities of Various Z_0 's, Using Tube Type 5718.

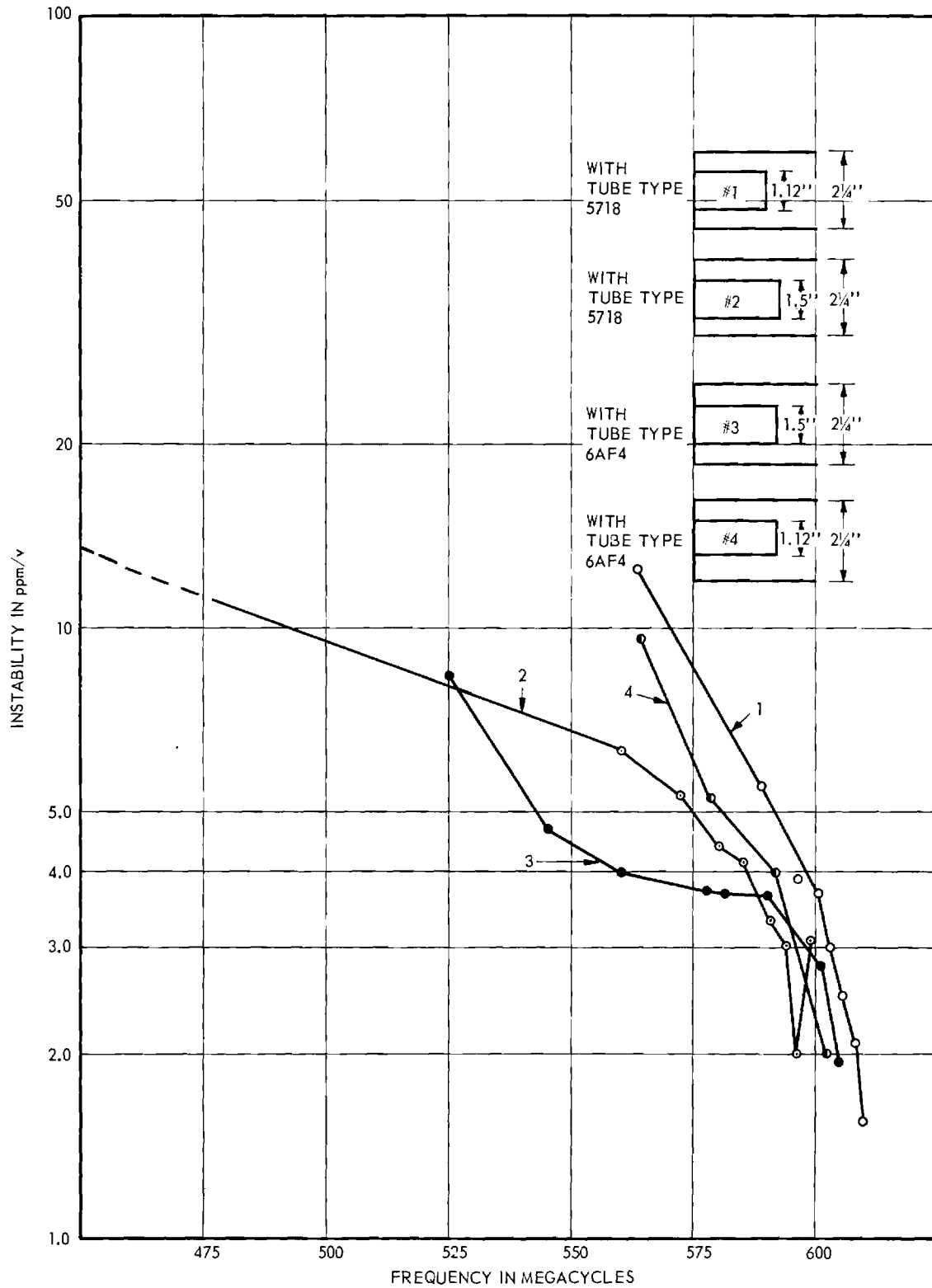


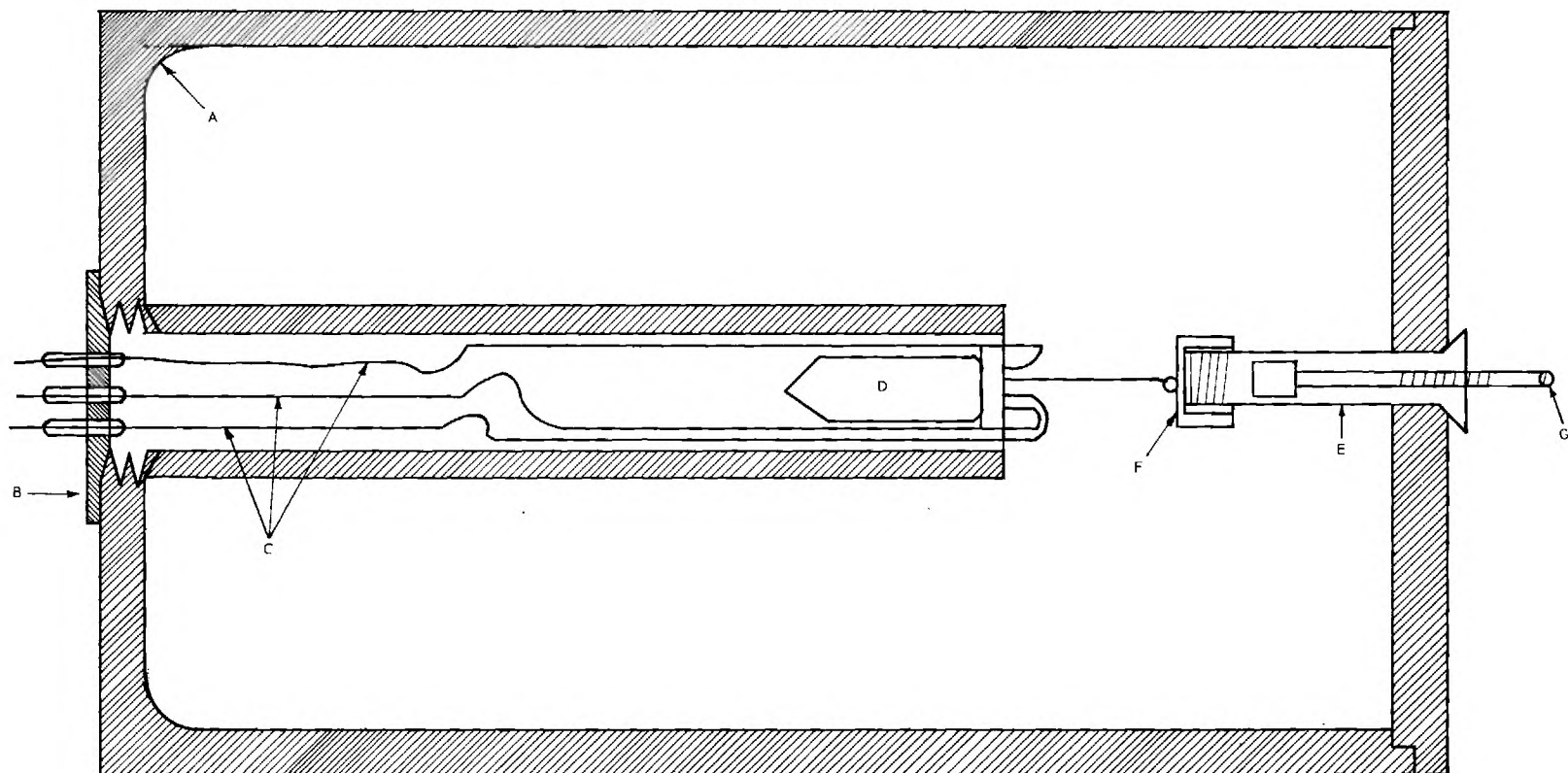
Figure 5.15. Stability Characteristics of Oscillators in Small Cavity.

D. Series-Capacitor Cavity-Controlled Oscillators Constructed of Invar

The information gained concerning the operation of series-capacitor-type cavity-controlled oscillators was next utilized in the construction of an Invar cavity and an associated tube. The choice of Invar as a base material stemmed from the fact that although temperature-compensated cavities have shown the least insensitivities to temperature, the construction and assembly of these units is, in general, difficult and expensive. Invar exhibits a temperature expansivity of less than 1 ppm/°C, and its use must be considered as a compromise between simplicity of construction and temperature insensitivity. However, the resulting cavity was not expected to be more than twice as sensitive to temperature variation as was the compensated type. Another compromise was made in the size of the cavity diameter since, as it was pointed out in the early part of this report, cavities are usually designed to have a Q which is optimum, consistent with space requirements.

The form and some details of the configuration selected are illustrated in Figure 5.16. The cavity was chosen to have an outer diameter of three inches in order to provide a satisfactory form factor and at the same time sacrifice little in stability characteristics. The inner conductor was selected on a basis of Z_0 and Q to provide the oscillator with the best theoretical frequency stability possible.

Hermetic sealing was provided at one end of this resonator by inserting a hermetically sealed socket within the center conductor. Electrical connection to the power leads are made through this seal, as illustrated in Figure 5.16. Sealing at the other end was effected by modifying the variable capacitor located there. In the oscillator of the same figure, a JFD VC-5 type condenser connects the plate of the tube to the end plate of the cavity. The capacitor has a cylindrical shell, which is normally open at one terminal. In order to seal this cylinder, a shaped cap in the form of a thin Invar shell was provided. This cap is then forced over the open end of the cylindrical capacitor and complete sealing is then effected by running sufficient solder into the cap in order to provide a firm union between cylinder and Invar cap.



- A. SINGLE PIECE OUTER CONDUCTOR
- B. HERMETIC SEAL AND POWER-SUPPLY FEED-THROUGH
- C. POWER LEADS
- D. TUBE TYPE 6AF4
- E. CAPACITOR, TYPE JFD VC-5
- F. INVAR CAP FOR HERMETIC SEAL
- G. TUNING CONTROL

Figure 5.16. Details of Invar-Cavity Oscillator.

The outer conductor and high-current (shorted) end of the coaxial cavity are formed of a single piece of Invar. This form was obtained by boring out a solid piece of three-inch-diameter Invar rod, terminating the cut at the shorted end. That end was drilled and tapped to accept the inner conductor which was under cut slightly as shown to provide good electrical conduction at this junction. The entire cavity was silver plated by techniques to be described in a subsequent section. A photograph of the complete oscillator is shown in Figure 5.17.

Methods of measuring the absolute frequency of this oscillator having an upper frequency was about 627 mc were not adequate at the time of its completion. For this reason, two oscillators were constructed which were identical in every respect except that one cavity was constructed of brass. The two oscillators, brass and Invar, were tested for stability-versus-anode variations as in all cases before and found to be identical. The short-term stability of these devices was then tested by tuning one oscillator to a frequency slightly different from the other so that a "beat frequency" could be obtained when the outputs were introduced into a high-frequency receiver. This beat frequency could be measured with less than three per cent accuracy by means of a cycle counter. Further refinement included a recording device (Esterline-Angus), which was fed from the output of the cycle counter.

In order to exclude external effects as much as possible, the entire test was conducted in a temperature-controlled room. Separate power supplies were used on the individual oscillators.

The results of a recording covering several hours is illustrated in Figure 5.18. The total relative frequency deviation during the first half-hour of the test is not in excess of 40 cycles (neglecting two very rapid changes which could have been due to noise in the receiver). This frequency change corresponds to a stability of $40/627 \times 10^6 = 7$ parts in 10^8 . The recording apparatus was left on overnight (a period of approximately 14 hours) as is shown in the second strip in Figure 5.18. The total deviation during this period is not over 300 cycles, which corresponds to a stability of not over 5 parts in 10^7 .

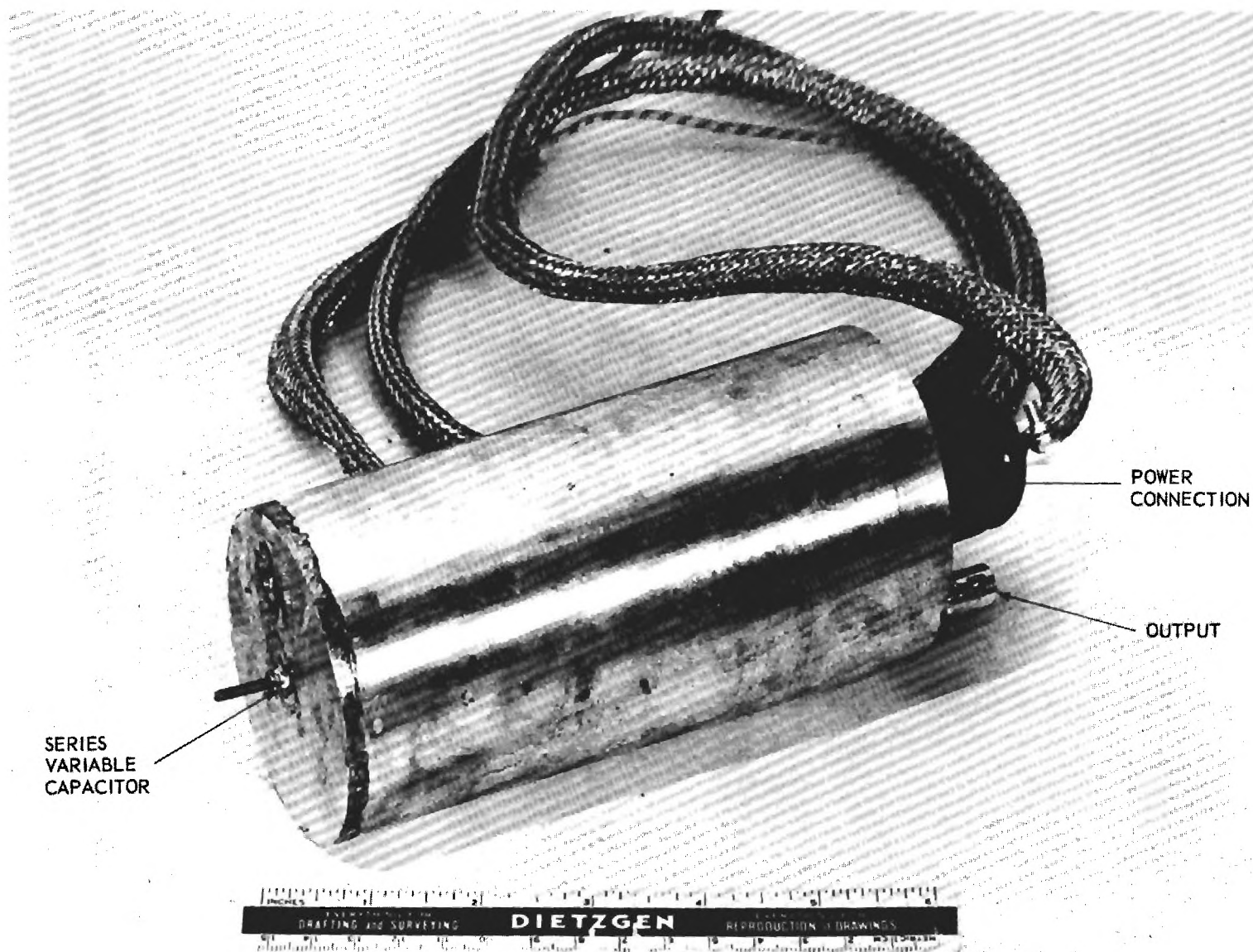


Figure 5.17. Photograph of Invar-Cavity Oscillator.

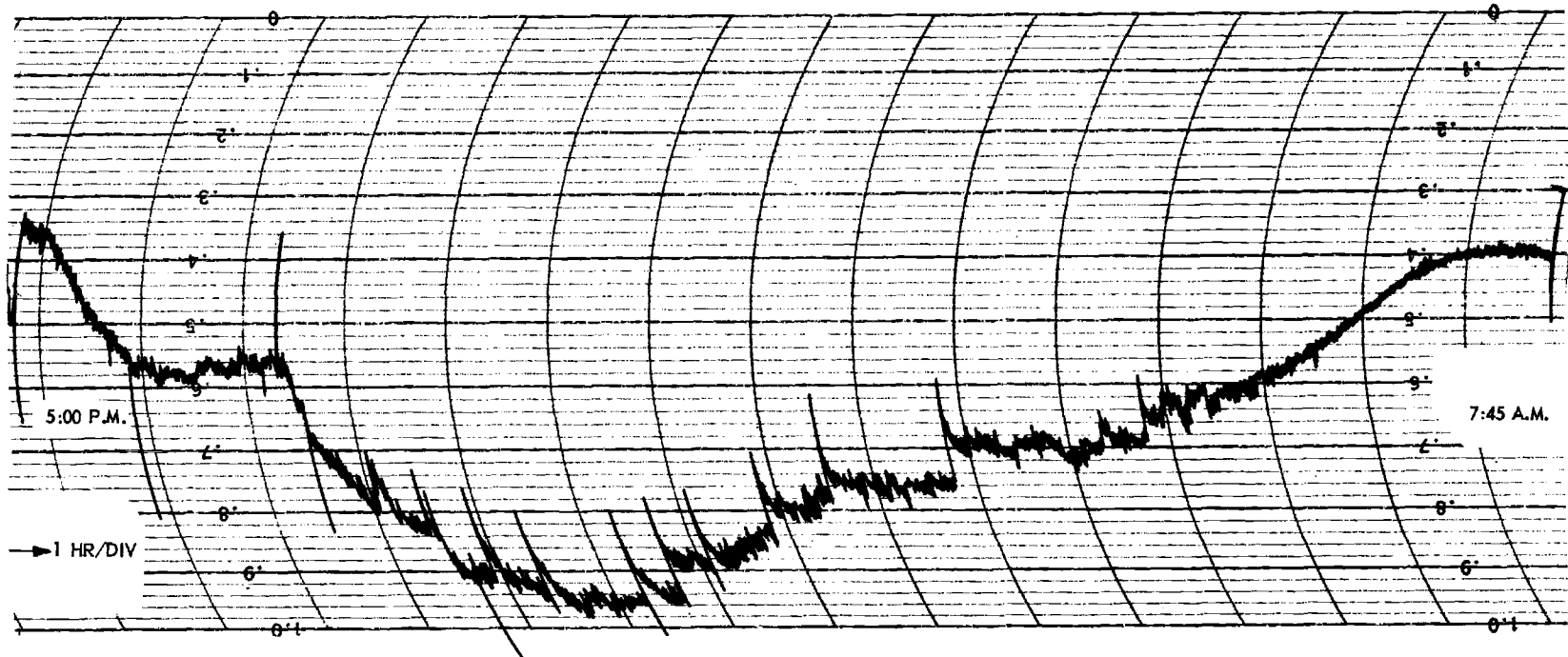
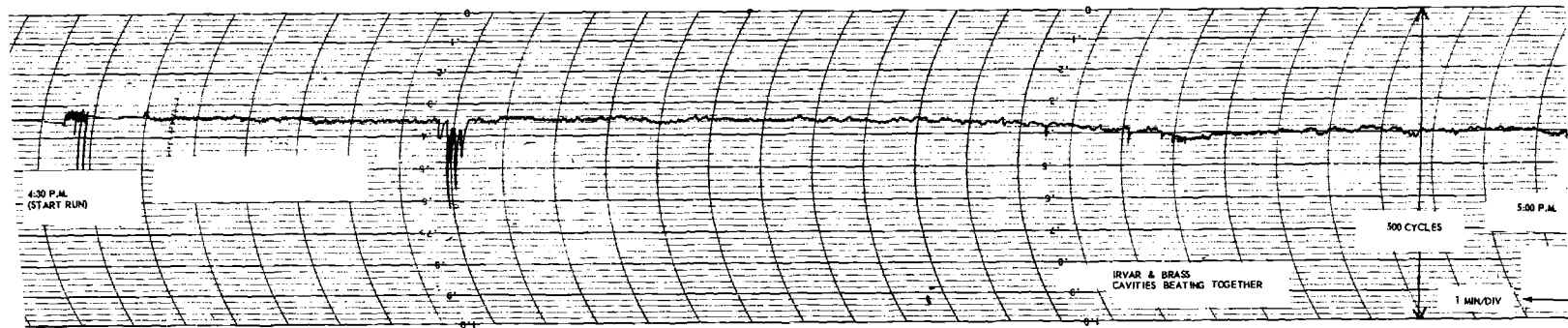


Figure 5.18. Recording of Beat Frequencies Between Two Cavity-Controlled Oscillators.

E. Effects of Temperature on Invar-Cavity-Controlled Oscillator

After the short-term stability of this oscillator had been tested, equipment was acquired with which absolute frequencies could be measured within 1 part in 10^8 . With this acquisition, tests were initiated to determine the temperature sensitivity of the oscillator. Prior to actual tests on the oscillator, an investigation was made of the temperature-gradient characteristics of an Invar cavity. The results, which appear in Chapter IV of this report, helped to predict the expected action of the oscillator.

A frequency-drift curve for the Invar-cavity-controlled oscillator, all the components of which were initially at ambient temperature and to which anode filament voltages were applied at zero reference time, is plotted in Figure 5.19. A very rapid frequency drift exists during the first five minutes, a drift amounting to about 30 kc. Thereafter the total drift is less than 14 kc. The drift during the first five minutes is perhaps attributed to the changes in the vacuum tube and is an indication of the over-all stability of the oscillator. The drift thereafter is almost wholly due to the thermal coefficient of expansion of the Invar which is approximately 1 ppm/°C. This is evident from Figure 4.17 where it was seen that an "average" temperature change for the inner conductor was about 20.5 ppm when the temperature finally reached equilibrium. This corresponds very closely to the 14-kc frequency change observed.

Another interesting test was performed by allowing the Invar-cavity oscillator to reach equilibrium in an ambient temperature of about 25° C. It was then immersed in an oven which had been maintained at 50° C for several hours. The frequency-versus-time data for these conditions are plotted in Figure 5.20. The surprising effect (noted on several attempts) is that the frequency initially rose to a maximum value and then after about 10 minutes dropped at a reasonable rate.

This effect is perhaps due to the fact that only the outer conductor temperature changes during the first 10 minutes, and that the expansion of the outer conductor lowers the capacitive end effect depicted by Figure 4.2. As the outer conductor expands, and the inner conductor does not, because of the high thermal lag, the effect of this capacity is reduced, thereby raising the frequency of

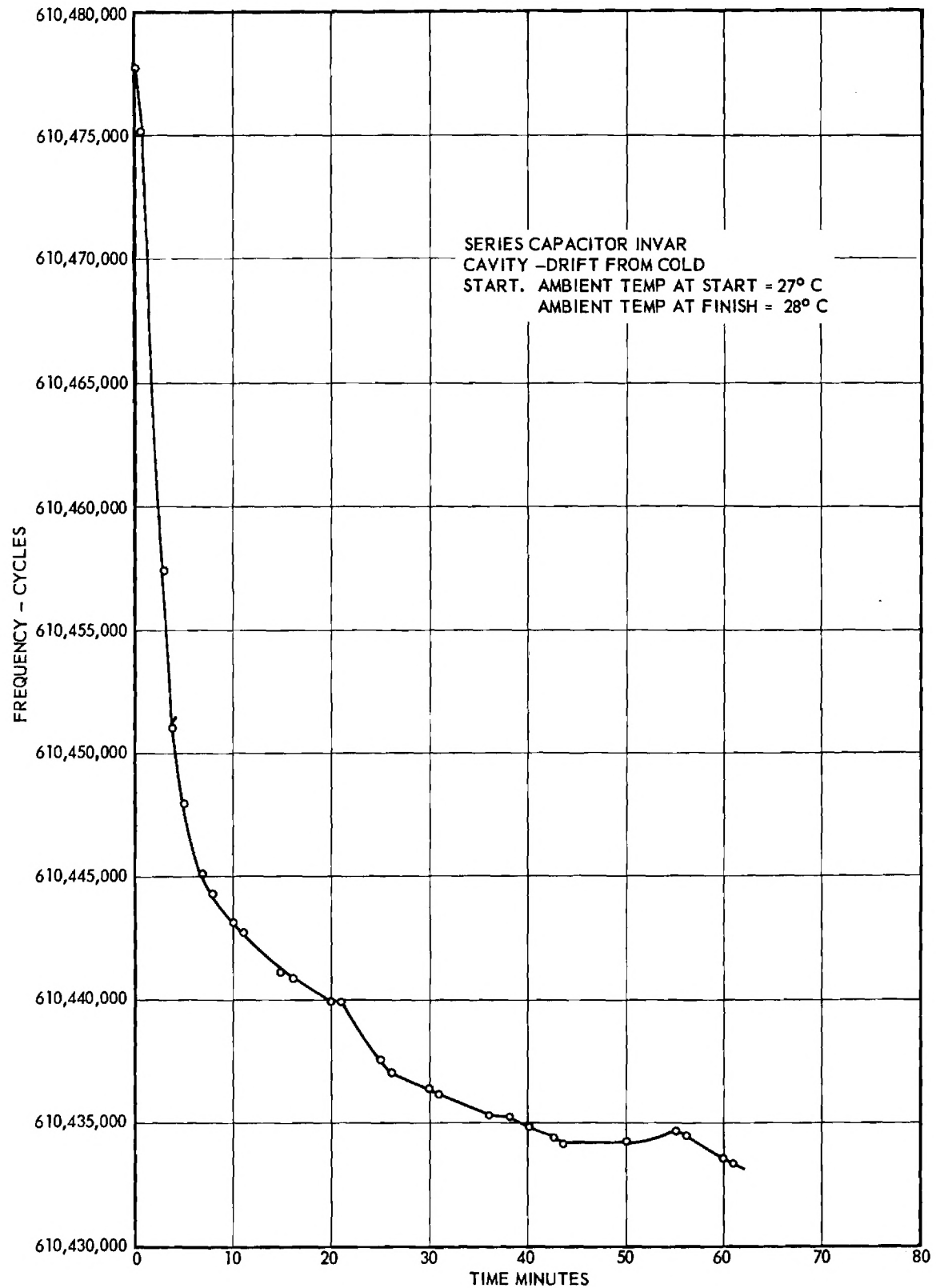


Figure 5.19. Frequency Drift of Series-Capacitor Invar Cavity During Warm-up.

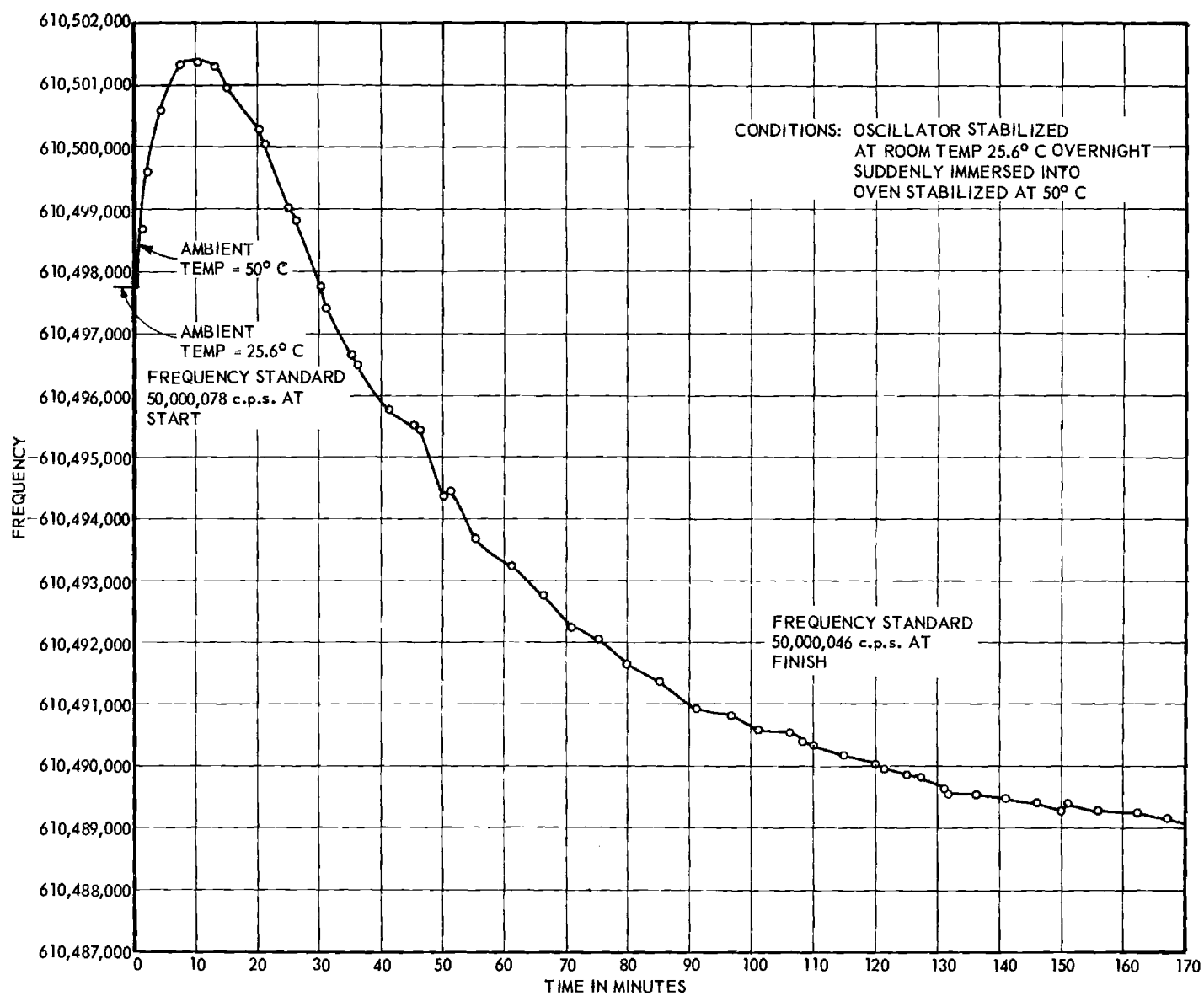


Figure 5.20. Effect of Abrupt Change of Ambient Temperature on Invar Cavity.

resonance. After 10 minutes, however, the inner conductor begins expanding at a rate sufficiently high to overcome the outer conduction expansion, and finally there is seen to be a drop in the frequency which continues for two or more hours before equilibrium is reached.

This effect was not experienced with the brass-cavity oscillator of the same dimension, probably due to the high heat conductivity which permits little lag between inner and outer conductor temperatures. If a fan moves air in the vicinity of the brass cavity, an immediate rate of drop in frequency is observed.

F. Effects of Small Filament Changes on Frequency of Brass- and Invar-Cavity-Controlled Oscillators

A comparison of the frequency change of the brass- and Invar-cavity-controlled oscillators is illustrated in Figures 5.21 and 5.22. Here the oscillators had been stabilized at normal frequency with normal voltages applied to both plate and filaments. After application of a voltage increment, the Invar cavity is seen to practically stabilize at 2.5 ppm away from the original frequency, while the brass-cavity-controlled oscillators show an immediate increase in frequency accompanied by a sharp drop which continues at nearly a linear rate for a considerable length of time. The data presented here were taken for 27 minutes on the brass-cavity oscillator, and no sign of a "level-off" is evident at 6.5-ppm frequency change.

G. Re-entrant Cavity with Pencil Triodes

The pencil triode appears to be one of the most attractive tubes for oscillators in the 500- to 1500-mc region. Attempts at using this type tube in the series-capacitor cavity-controlled oscillator produced disappointing results. The inherent low ratio of output-to-input capacitance of the tube makes it an excellent amplifier. In an oscillator, however, a high ratio of output-to-input capacitance is desired to produce enough feedback for sustained oscillations. Positive feedback was incorporated to increase the grid drive, but this did not particularly improve the results.

Therefore, it was decided that an arrangement similar to that used in conjunction with the lighthouse tube might be used. Some of these arrangements are shown and discussed in Reich's (5) text. One of these, a form of re-entrant cavity is shown in Figure 5.23.

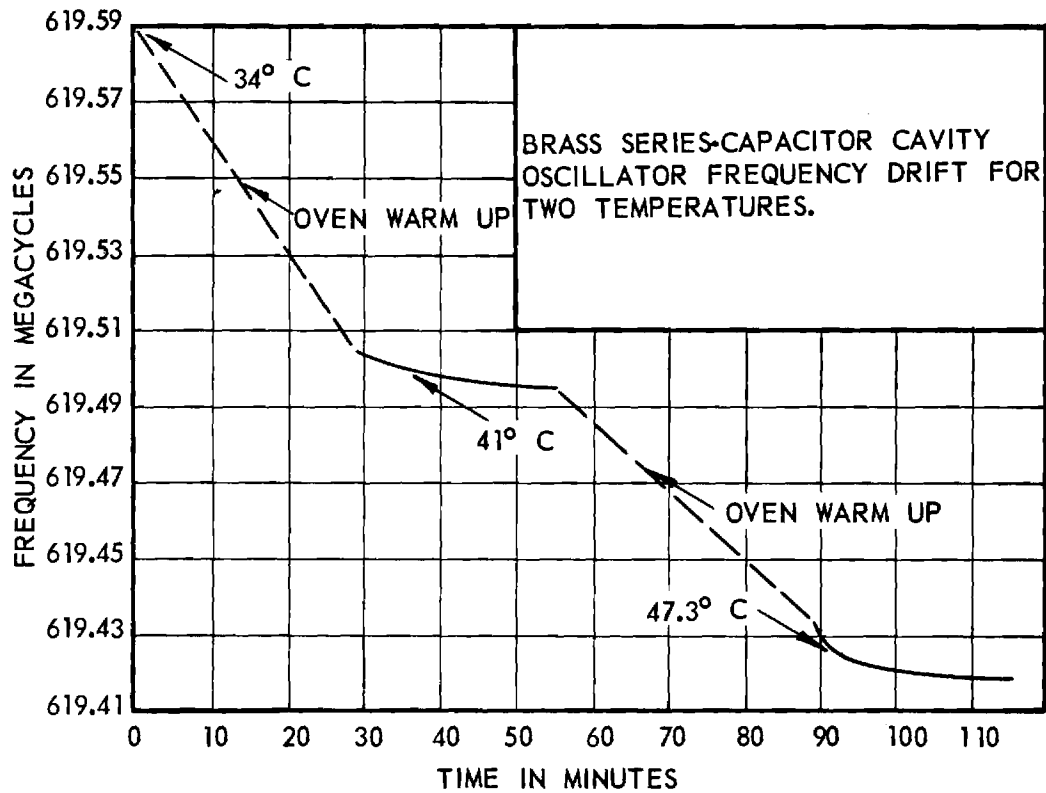


Figure 5.21. Temperature Effects on Brass-Cavity-Controlled Oscillator.

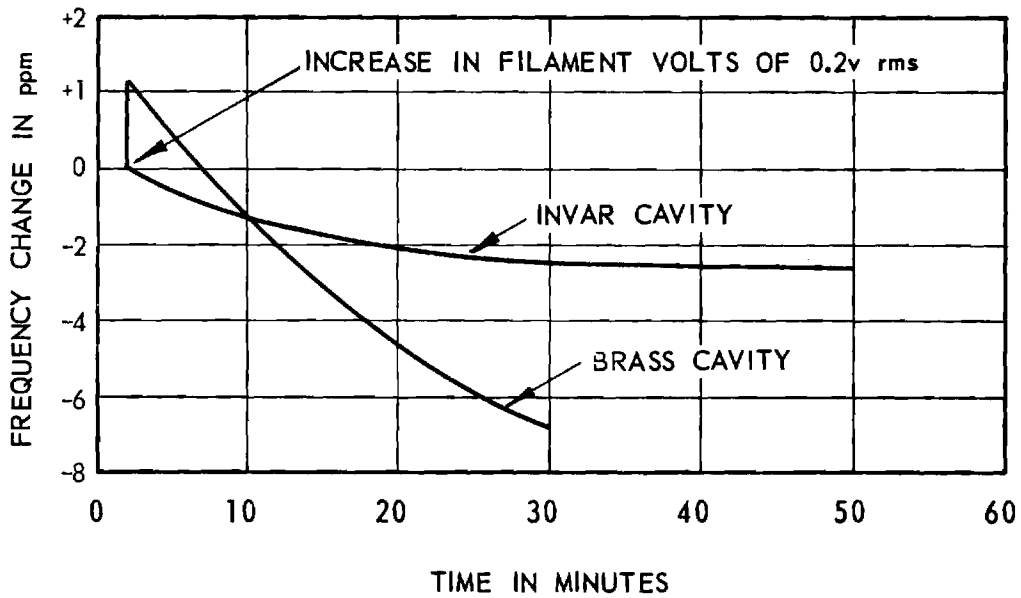


Figure 5.22. Comparison of Filament Voltage Effects on Brass and Invar Cavities.

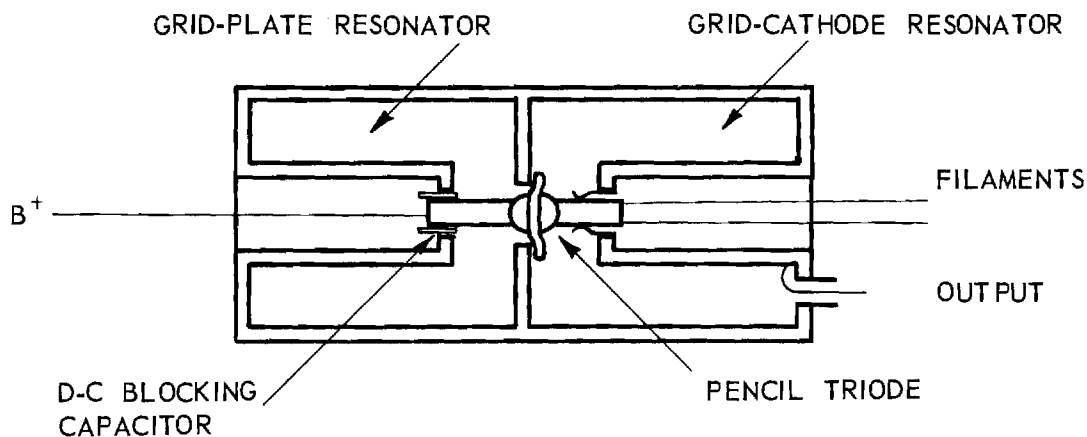


Figure 5.23. Re-entrant Type Cavity Using Pencil Triode.

The grid is shown at d-c ground potential in this arrangement. The only source of feedback in this circuit is the plate-to-cathode capacitance, a quantity which is very small in the pencil triode type 5876. The lumped-element equivalent of this circuit is shown in Figure 5.24.

Referring to Figure 5.23, it is seen that energy can be coupled from the plate-grid resonator to the grid-cathode resonator by placing holes in the ring which supports the grid. Following the reasoning set forth in the construction of the series-capacitor type of oscillator arrangement, it was thought that capacitive coupling of the grid to this ring might increase the reactance slope in the manner previously evidenced. If the grid signal is to be derived through capacitive coupling, it must have some sort of conductive coupling to the cathode providing a d-c path for grid current. An arrangement which furnishes a-c and d-c continuity is shown schematically in Figure 5.25.

The tuning screws are used to vary the amount of capacitive coupling to the grid. It can be seen that as the screws are inserted into the cavity, the energy feedback between the two resonator sections will be decreased, since the reduced opening results in a decrease in mutual coupling. The lumped element of the arrangement shown in Figure 5.25 is illustrated in Figure 5.26.

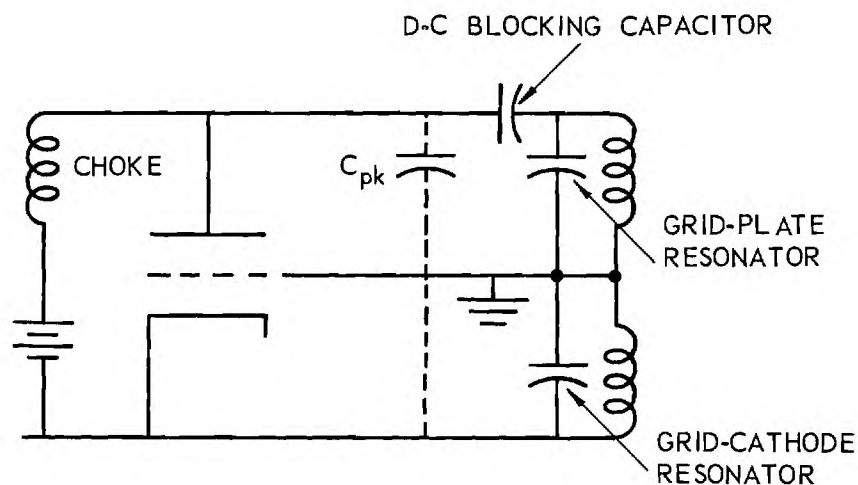


Figure 5.24. Lumped Equivalent of Re-entrant Cavity and Triode.

Here the effect of the tuning screws is seen to vary the coupling between the resonators and also to vary the capacitance coupling to the grid. These two effects are, of course, inversely related. That is, as the capacitance is increased, the mutual coupling is decreased.

The tuning screws, while capable of fine adjustment, were found to be mechanically unsatisfactory. In place of these tuning screws, various sizes of washers were clamped to the grid. One of the actual models tested is shown in the accompanying photographs, Figures 5.27, 5.28, and 5.29.

In Figure 5.27, these washers, which shall be called irises, are shown in detail. In addition, the method in which they are clamped to the grid of the tube is represented. Five discrete sizes of irises were tested, and finally in the last test, the iris was completely removed.

Figure 5.28 shows an exploded view of the oscillator assembly. Parts B and F are the sections of the outer conductor. Parts A and B make up the grid-cathode resonator, while parts F and G make up the plate-grid resonator. Part C is a molded and machined cylinder of Scotch Plasticast serving the purpose of supporting both the pencil triode D and four 4.7K resistors in parallel around the grid structure. One of the irises, part E, is shown. This is also held in place on part C and serves the additional purpose of holding the tube in place. Part H

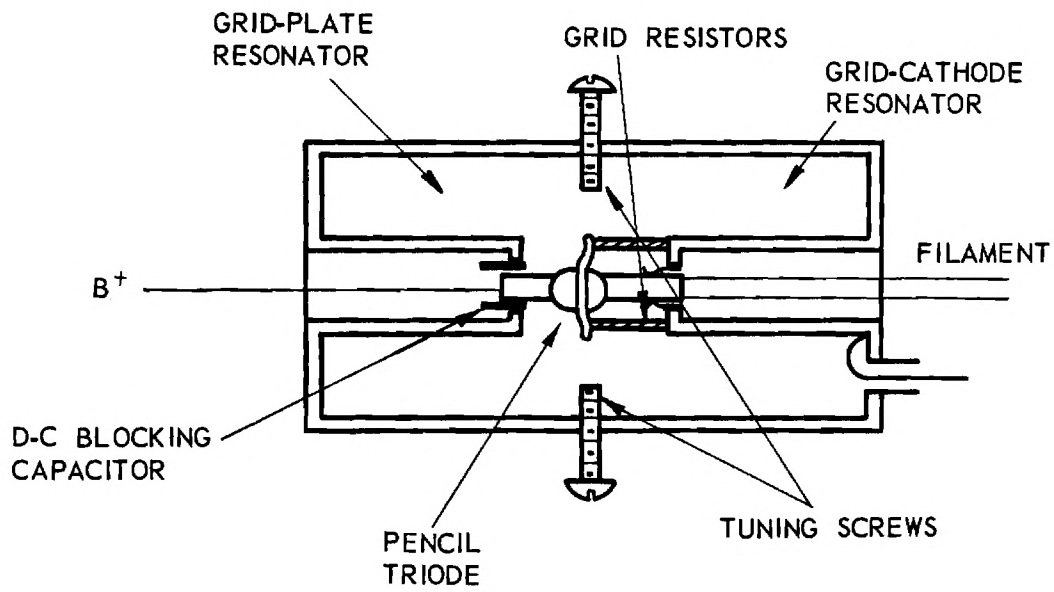


Figure 5.25. Capacitively Coupled Re-entrant Cavity.

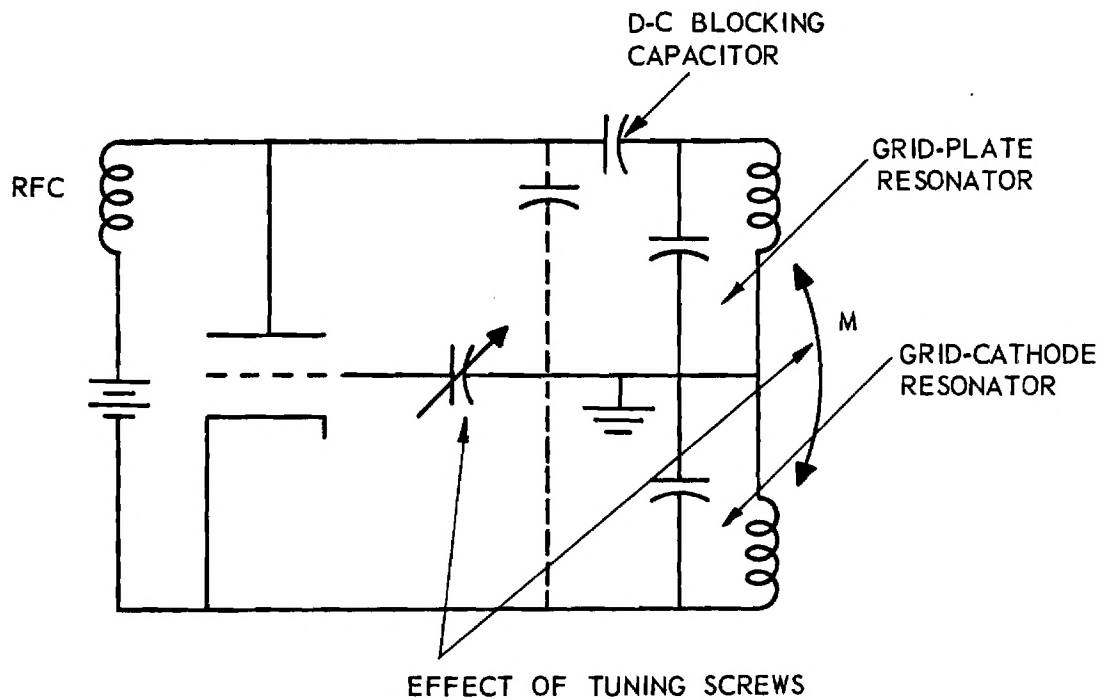


Figure 5.26. Lumped Equivalent of Capacitively Coupled Re-entrant Cavity.

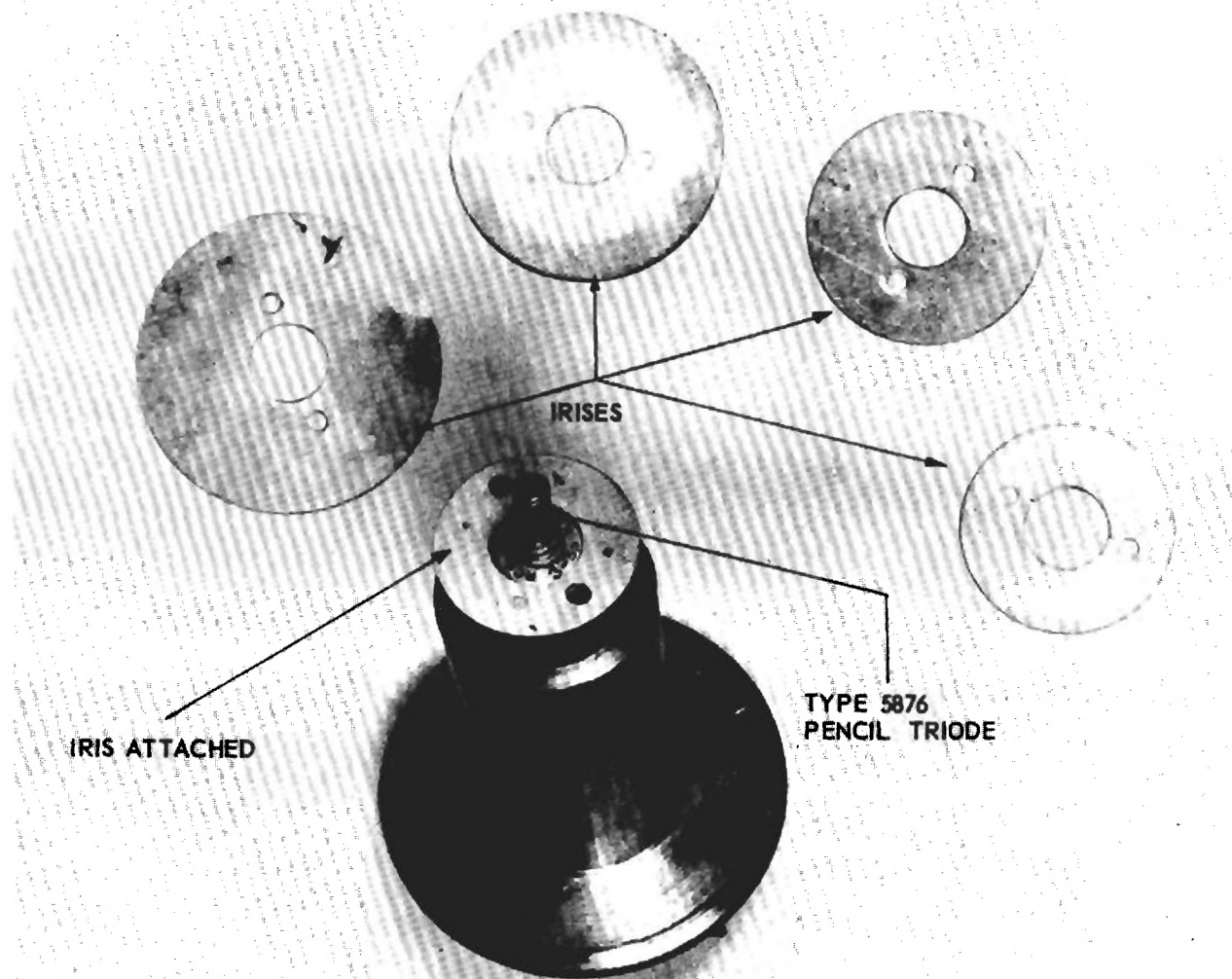


Figure 5.27. View of Iris Sizes and Grid Connection in Re-entrant Cavity Oscillator.

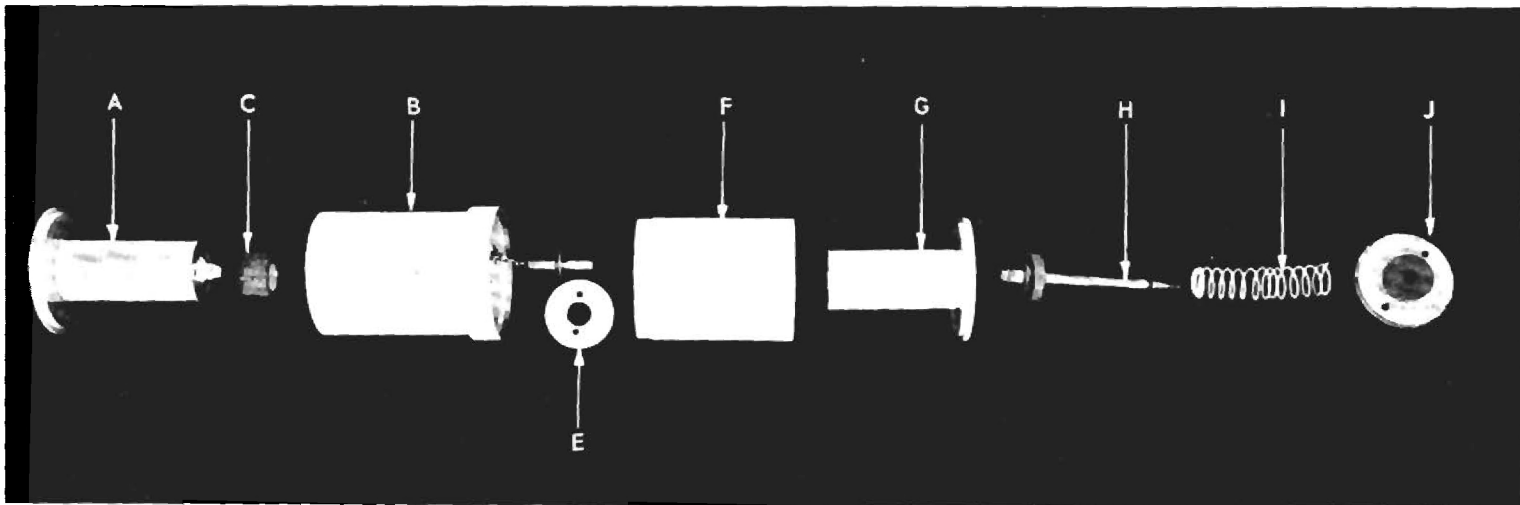


Figure 5.28. Exploded View of Re-entrant-Cavity Oscillator.

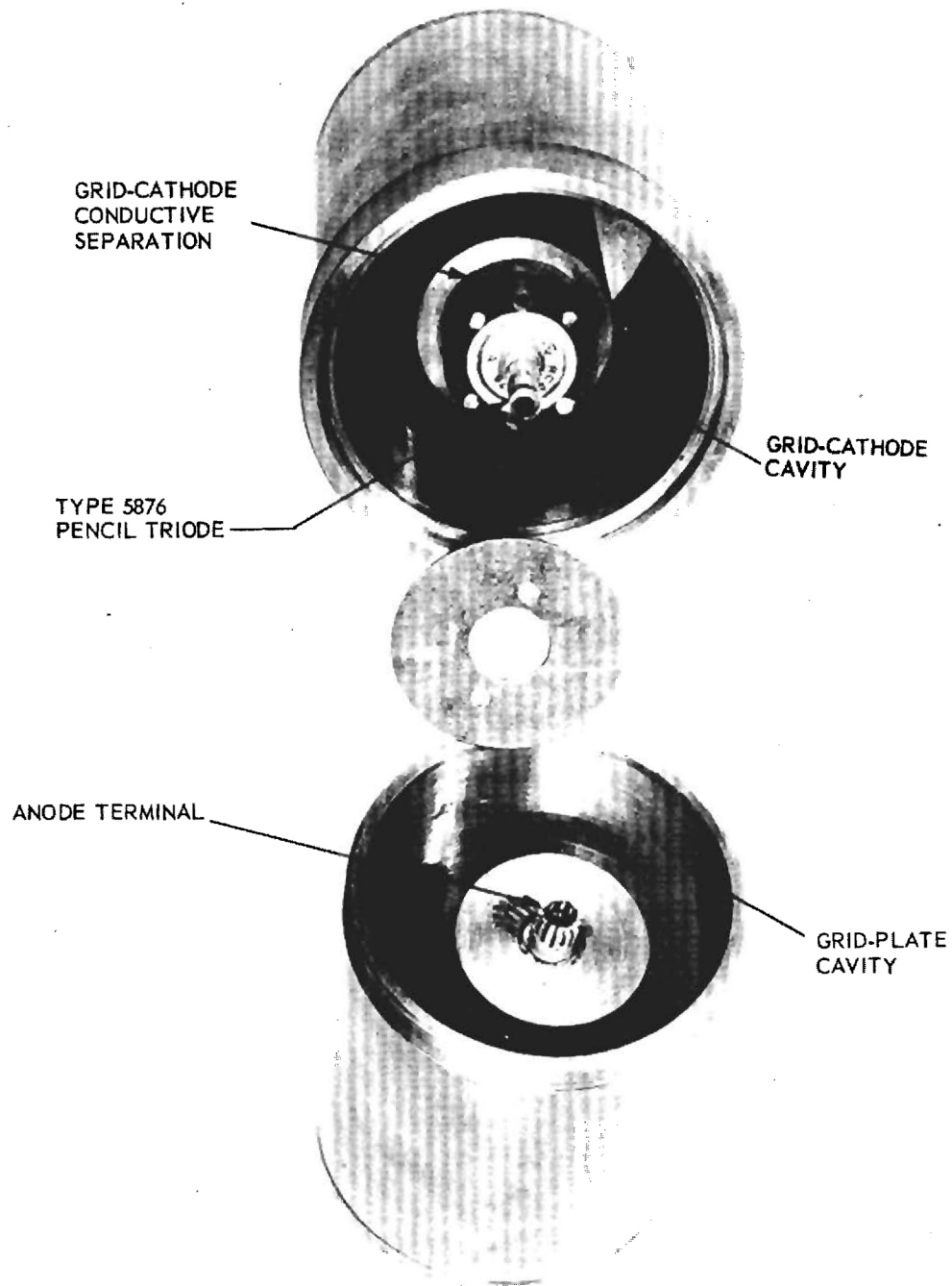


Figure 5.29. Semi-Assembled View of Re-entrant Cavity Oscillator.

is inserted into G and serves as conductor for the plate supply voltage. A small ceramic washer on the left end serves as a by-pass condenser of 75 μf capacity. Another by-pass condenser in the form of a feed-through is seen on the right end of the picture. Part I is a spring which exerts pressure on H so that the ceramic washer will make good contact on the inside of G. Finally part J serves to support the right end of H and to maintain pressure on the spring. A semi-assembled view of the arrangement is shown in Figure 5.29.

A cross section of the assembled oscillator with dimensions, is shown in Figure 5.30. As before, the section on the left of the drawing is the cathode-grid resonator, while that on the right is the plate-grid resonator. The construction was designed in this way to permit the tuning screws to be placed in the coupling sleeve. A more important reason, however, was for ease of assembly and disassembly. This particular oscillator operated at a maximum frequency of 650 mc.

The pencil triode is often a very delicate tube type and is easily broken. For this reason, accurate alignment of supports is required. The dimensions on this sketch are shown to three decimal places allowing ± 0.005 -inch tolerance in normal shop practice.

The plate supply lead is brought in through the inner conductor of the plate-grid resonator and is by-passed at both ends as previously mentioned. The oscillator was tested with each of the five irises and also without an iris. Various plate voltages were used in checking the stability as a function of anode potential. The results of these tests are shown in tabular form in Table 5.2. It can be seen that the frequency is highest with no iris, and the frequency stability is best under these conditions. This corresponds to high mutual coupling between resonators and low capacitive coupling to the grid.

The encouraging results obtained with this configuration operating in the 600- to 650-mc region led to the construction of two additional oscillators to operate in the 800- and 1000-mc region, respectively. No significant changes in the construction of the 800-mc oscillator were made as compared to the 650-mc oscillator other than the insertion of an output loop connected to a BNC-type connector at the cathode end of the structure.

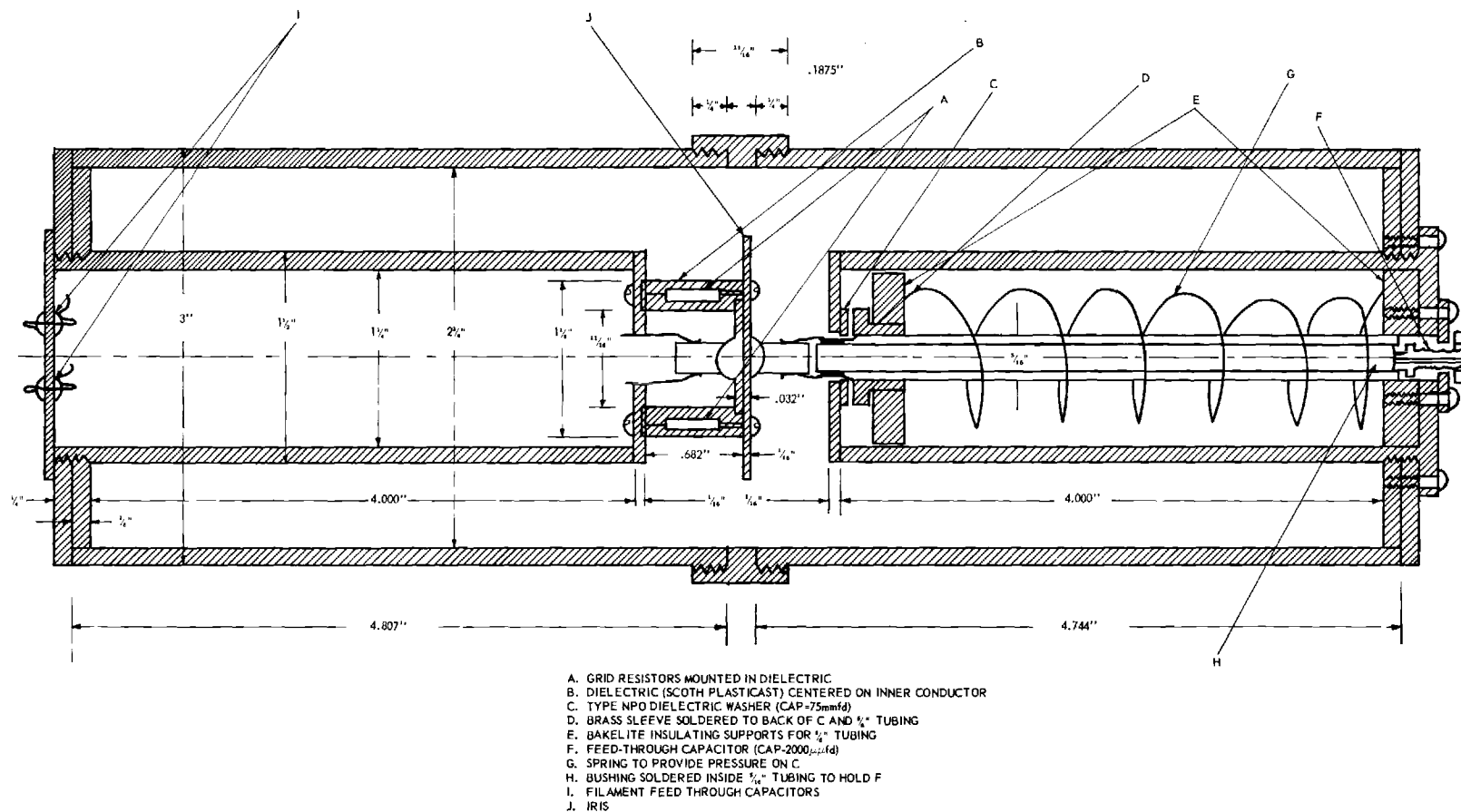


Figure 5.30. Cross Section of Assembled Re-entrant Cavity Oscillator.

TABLE 5.2

RE-ENTRANT TYPE CAVITY STABILITY VARIATIONS
WITH IRIS SIZES AND PLATE VOLTAGE

<u>Iris Size</u>	<u>Plate Volts</u>	<u>Plate Current</u> (ma)	<u>Frequency</u> (mc)	<u>Stability</u> (ppm/v)
None	200	13	650	3
None	250	16	650	1.5
None	300	20	650	1.5
1 (smallest)	200	12	647	3
1	225	14	647	2
1	250	16	647	2
2	200	12	643	4
2	225	14	643	3
2	250	17	643	2
2	300	22	643	2
3	200	12	638	4
3	225	14	638	2.5
3	250	17	638	2.5
3	300	23	638	2.5
4	200	13	624	5.5
4	225	17	624	3.5
4	250	20	624	3
4	275	23	624	3
5 (largest)	150	8	612	10
5	200	14	612	3.7
5	225	17	612	3.1
5	250	20	612	2.6

The possibility of tuning the plate-to-grid cavity or the cathode-to-grid cavity in order to gain the optimum results was considered. For this reason, a tuning screw was included in the 800-mc oscillator.

The 1000-mc, re-entrant cavity differed from the 600- and 800-mc cavities which were made with separate plate-to-grid and grid-to-cathode outer conductors. These resonators were mechanically coupled by a sleeve. The primary purpose of the mechanical sleeve had been for use as a base for inserting tuning screws, but these screws have been superseded by "irises" in later models which have the purpose of changing the grid drive and of changing frequency. In the new configuration, it was expedient to discontinue the use of the sleeve and to construct the outer member of a continuous piece of brass tubing.

Several sizes of irises, flat rings extending the grid diameter, were used in the 800-mc cavity oscillator. Different values of grid resistance were also employed. In Figure 5.31, the results of a few tests are plotted wherein iris sizes and resistor sizes appear as parameters. The instability of the oscillator is seen to be reduced when the plate voltage is increased, exactly as occurred in the earlier 600-mc oscillator. The instability is also reduced as the iris size is made smaller, and finally the combination of highest plate voltage and no iris at all resulted in the best stability of all those illustrated.

It was not possible to make the configuration oscillate when no iris was present and with the grid resistance reduced to 1200 ohms. However, grid resistors of 1700 and 2200 ohms did allow the circuit to oscillate when no iris was in place. The use of the 1700-ohm grid resistor resulted in slightly better stability than was evidenced during the use of the 2200-ohm resistor. The plate dissipation was very high in both cases, thus indicating that the grid drive, and hence grid bias, is greatly reduced and that the tube operates into a very low conductance.

The addition of the iris resulted in greater grid drive, a condition indicated by lower plate current. The lowest plate current and the lowest frequency were obtained when the largest iris was employed. The oscillating frequency for each case is indicated on its respective curve.

After conclusion of these tests, the output loop and tuning screw in the cathode-grid resonator were installed. It was found necessary to add an iris in order to obtain sufficient output to be measured with a 0-1-volt, vacuum-tube voltmeter. The frequency of oscillation was 781.5 mc before insertion of the tuning screw, but as the screw insertion was increased the frequency was lowered to a minimum of 767.9 mc at which point oscillations completely ceased. The instability of this arrangement was nearly constant at all positions of the tuning screw until the tube stopped oscillating.

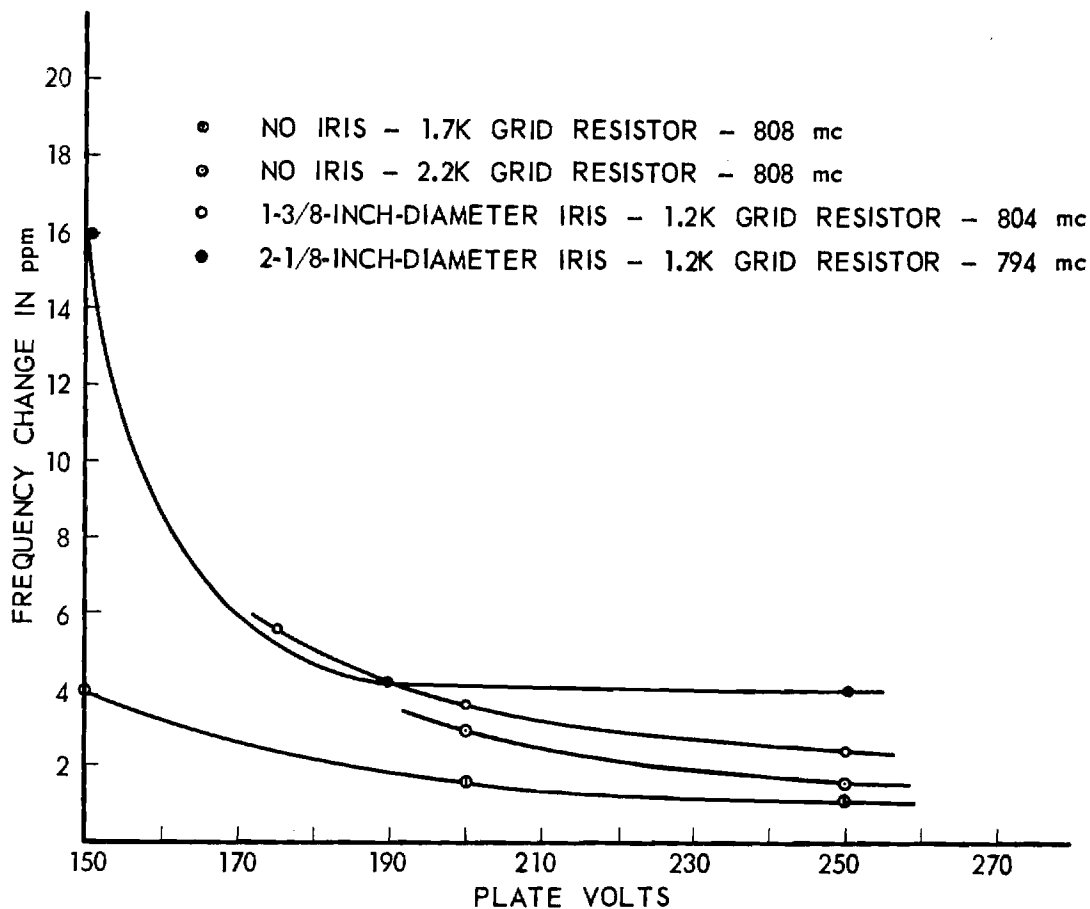


Figure 5.31. Results of Stability Tests on 800-Mc Oscillator.

A final test involved the effects of filament voltage. The filament voltage was changed in a single step by 0.3 volt from the normal level of 6 volts. First the circuit was completely stabilized, then an incremental change was

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applied. There was an immediate decrease in frequency of 3500 cycles when the voltage was increased 0.3 volt, and approximately the same increase in frequency for an equal decrease in voltage.

VI. METHODS OF PLATING AND SOLDERING MATERIALS IN CAVITY RESONATORS

A. Introduction

Chapter IV contained a description of several coaxial cavities which were designed to serve as high-Q resonators. The discussion implied that the metallic surfaces had the highest practicable conductivity in order that a high value of Q could be obtained and also implied that secure mechanical bondings existed between component parts.

Some of the most important details in cavity construction are concerned with methods of plating the materials and with bonding the components in a firm and, usually, airtight enclosure. Soldering is one method of bonding which can satisfy both requirements of firmness and airtightness, but the types of solder required and techniques of application are somewhat dependent upon the materials being processed. This chapter discusses the combined problem of plating and soldering as applicable to several materials which have been employed in coaxial-cavity resonators and cavity-controlled oscillators. Silver has been used exclusively as the final surface but the problems of obtaining a firmly adherent, highly conductive surface are presumed to apply equally well to the other noble metals which are conventionally used in high-frequency resonators. The previous chapters stated that temperature-compensated cavities usually employ a glass or ceramic center conductor while the outer conductor may be of Invar or of brass. The methods of plating the various surfaces, the precautions required, and observations noted are included in the following sections.

B. Technical Details of Methods of Plating and Soldering of Materials Employed

1. Plating of Glass- or Ceramic-Based Materials

Silvered surfaces were utilized exclusively in all the resonators constructed and tested. The plating methods used on Pyrex, Stupalith, and Vycor are essentially alike. The steps involved and the precautions necessary are summarized as follows:

- (1) Remove any uneven or badly discolored spots on rod or tubing by a non-conductive abrasive, such imperfections will not retain a silvered surface.

(2) Clean material thoroughly of grease and dirt by scrubbing with detergent. Remove detergent thoroughly by copious rinsing.

(3) Bake ceramic materials at 350° F, or above, for two hours to remove all traces of absorbed moisture.

(4) After the material has cooled to approximately room temperature, spray with silver-based air-drying paint such as DuPont No. 4760 Silver Paste which has been thinned by Toluol to proper consistency for application by spraying.

(5) After two hours air-drying, place in oven and raise to 1250°-1350° F for 1/2 hour; cool in oven to 450° F, then remove and air-cool to ambient temperature.

(6) Inspect surface with a 5 to 10 power glass. If necessary, remove hills and pits with five abrasive. A mirror-like finish is required to insure a final satisfactory conductor.

(7) Porous ceramic surfaces which are not to be plated, but will come into contact with the solutions should be masked off with a good grade of lacquer which will not be affected by HCL.

(8) Electroclean 1 minute at about 8 volts. A wire soldered to an outside surface will permit this process as well as the plating to follow. Rinse with tap water.

(9) "Pickle" in a 30 per cent HCL solution. Rinse again with tap water.

(10) "Strike" plate at a high current (about 15 to 25 amps per square foot) for 30 seconds. The surfaces should be completely coated with Ag after strike. Rinse with tap water. The Ag "strike" solution should be composed of:

8 to 10 oz. NaCN per gal. of solution

.1 to .2 oz. AgCN per gal. of solution

(11) Silver plate in an agitated cyanide solution at 5 to 10 amps per square foot until the desired thickness is obtained. The solution should be held at about 30° C. Upon completion of plating, rinse with tap water again.

2. Plating of Invar

No special treatment is necessary other than that normally performed on ferrous materials. The steps in plating used are:

(1) Remove imperfections on surface with an abrasive, clean with a strong detergent and rinse well with tap water.

(2) Electroclean 1 minute at about 8 volts. A wire soldered to an outside surface will permit this process as well as the plating to follow. Rinse with tap water.

(3) Any portions (such as screw threads) that should not be plated are masked off with lacquer.

(4) Follow steps (9) through (11) in part B-1.

3. Soldering Techniques

Particular care must be exercised in soldering to silver-plated materials whose base is of glass or ceramic. Most common solders such as tin-lead, indium, silver-enriched tin-lead, Cerrobend, etc., have the undesirable property of contracting significantly during solidification. This contraction may easily strip the silvered surface from the base. The use of solder of minimum contraction reduces or eliminates this difficulty. One example of a satisfactory solder is found by the name of Cerrotru (58 per cent Bi and 42 per cent Sn), which has a melting point of 281° F. This solder readily receives electroplated silver, hence soldered joints may be given a final silver surface.

This solder may be applied by a small iron which concentrates heat at a point or by flowing it onto a surface which has been raised by oven-heating to a temperature equal or greater than the melting point of solder. The preliminary application of a flux such as Nalco-14, manufactured by the National Lead Company, results in improved adhesion of the solder.

C. Physical Characteristics of Plated Surfaces

All conducting surfaces in the coaxial resonators described above were formed from electroplated silver. These surfaces were placed directly upon the base material, in the case of Invar, or upon a fired conductive silver surface in the case of Pyrex, Vycor, and Stupalith.

Observations made over a two-year period indicate that these silvered surfaces, when applied according to the rules formulated in section B, adhere firmly and demonstrate satisfactory electrical properties. Exceptions to this statement were observed in special cases, described as follows:

(1) Two 600-mc compensated coaxial cavities, employing Pyrex center conductors, evidenced a decrease in cavity Q after three months' operation. Investigation revealed loss of silvered surface at the pressure points of the spring-finger contacts.

(2) The silvered surfaces on several elements which employed Stupalith as a base material were subject to bubbling, flaking, and fracturing under the influence of high ambient temperature.

The exceptions seem to be due to improper preparation of the surfaces or to absorption of gases or liquids in the porous base material inasmuch as no recently constructed resonators have demonstrated unsatisfactory characteristics in their plated surfaces. Therefore it has been concluded that careful attention to the steps and precautions of section B will result in the formation of satisfactory silvered surfaces on those base materials described.

Silvered surfaces on Pyrex have not been adversely affected by sliding pressure. A tunable compensated cavity employing sliding contact fingers was cycled and recycled many times over a period of months, but the characteristics of the cavity remained essentially constant throughout the period of tests.

The effect of humidity upon these surfaces has been observed but no precise evaluating tests have been conducted. However, no demonstrated significant effects upon the silvered surfaces due to humidity have been evidenced. Humidity is highly undesirable in a resonator because the added dielectric losses degrade the cavity Q and may cause changes in the resonant frequency of the cavity. It is therefore concluded that hermetic sealing is very desirable if high- Q , stable cavities are to be formed.

The silvered surface of the inner conductors of the cavities mentioned in section C-1 are shown in Figure 6.1. The areas of pressure contact by the spring fingers are clearly evidenced in both photographs. If similar losses of silver

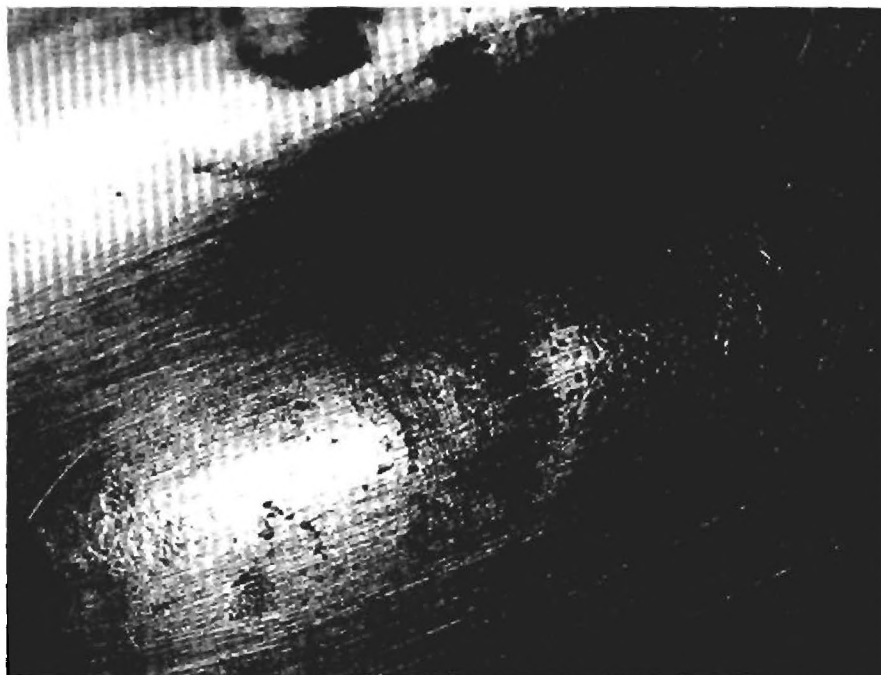
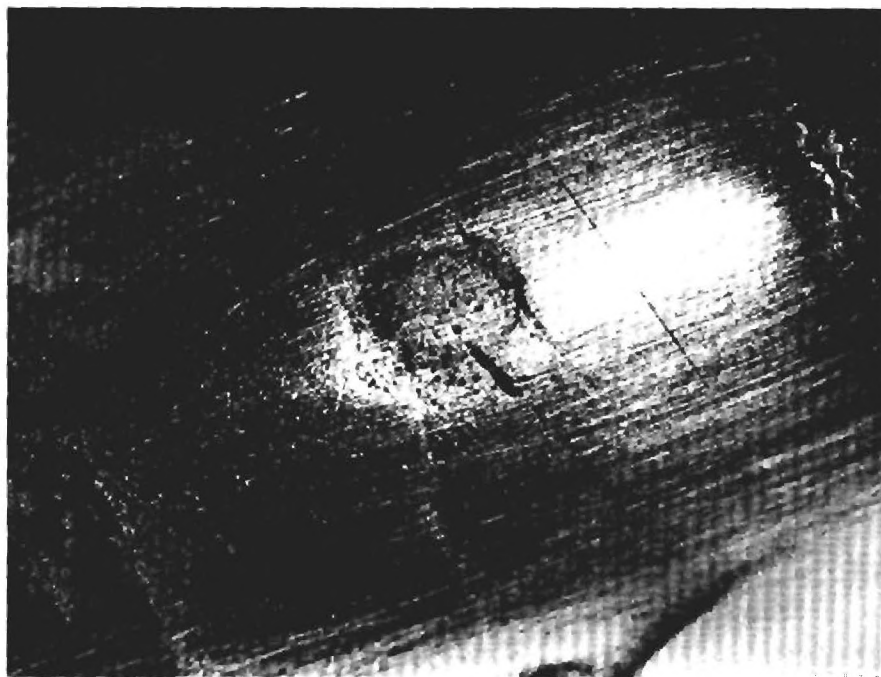


Figure 6.1. Photographs Showing Loss of Silvered Surface of Inner Conductor.

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had occurred in other resonators of the same type, then the spring-finger contact method of completing electrical union would have been considered completely unsatisfactory. However, other similarly constructed resonators have operated satisfactorily over long periods of time and have shown no evidence of comparable loss of silvered surfaces.

VII. VARIOUS MEANS OF CONTROL AT UHF

A. Introduction

The previous chapters of this report have discussed the applications of coaxial cavities and of cavity-controlled oscillators as frequency-control devices in the region above 500 mc. It was shown that those oscillators in which the associated vacuum tube is internal to the cavity are preferred. Two versions of this variety were discussed in some detail in Chapter V.

A variety of other means exists for providing frequency control at high frequencies. A number of devices designed to provide fixed- or variable-frequency oscillators have been examined during the course of the investigations undertaken by this project. Examples of devices or methods given specific study include high-frequency discriminators and reactance tubes in afc, synchronization of oscillators by special forms of signal voltages, and utilization of modified butterfly units as oscillator tuners at frequencies above 500 mc.

Several examples have been cited in progress reports already submitted by this project, and each method of frequency control was shown to possess some desirable characteristics. However, many of the oscillators demonstrated frequency stabilities which compared unfavorably with the stabilities of the preferred cavity-with-tube types first mentioned. Others presented technical problems which could not be simply resolved. For these reasons, and also because a higher priority had been attached to those cavity-controlled oscillators described in Chapter V, each of the presently discussed investigations was inactivated in order that greater effort might be devoted to high-priority topics.

The following sections of this chapter describe several devices or processes which may be employed in frequency control at high frequencies but which have been incompletely tested for reasons stated previously. The information listed is designed to serve as either general information relative to high-frequency control or a prelude to more extensive studies of a particular device.

B. High-Frequency Overtone Responses of Quartz Crystals and Their Application

A previous project included investigations of nuclear quadrupole resonances in a variety of materials. In the course of this study, it was observed that

piezoelectric quartz crystals may display considerable mechanical and electrical activity at relatively high frequencies. To study this phenomenon a technique was employed wherein a loop of wire was connected across the terminals of a mounted AT-cut quartz crystal and this loop was placed in the vicinity of the tank-coil of an f-m detector. Excitation of the crystal at any specific frequency resulted in absorption of energy at that frequency and a change in plate voltage of the detector. The absorption action was then observed on an oscilloscope.

The principal component of the apparatus used in conducting this study is the f-m oscillator shown in Figure 7.1. This oscillator is similar in principle to those previously used by this group in their work on nuclear quadrupole resonances. The resonant circuit is a shorted transmission line with a small variable capacitor across the open end providing a means of fine tuning and a driven capacitor (wobulator) providing the frequency modulation. The output of the oscillator is obtained by conventional means and fed to the vertical deflection plates of an oscilloscope. The frequency range of the oscillator is approximately from 200 to 350 mc. There is a dead spot in the range from 210 to 230 mc, and above 290 mc the oscillator radiates several frequencies simultaneously. However, the latter anomaly in the oscillator's behaviour can, by means of proper measuring techniques, be reduced to nothing more serious than a time-consuming annoyance.

The crystal under test was coupled inductively to the resonant line by means of a fixed rectangular loop parallel to and near the line. When the oscillator was swept by the wobulator through an overtone frequency of the crystal, a spike, or a differentiated spike, was observed on the oscilloscope. See Figure 7.2 A for example.

To measure the amplitude of the response, the height of a spike was first observed. Then a Hewlett-Packard audio oscillator was connected across the transmission line and its output level adjusted until the deflection on the scope was the same as that produced by the signal. The output voltage of the audio oscillator was then measured by a comparison between the deflection it produced when connected directly across the scope and the deflection produced by the internal calibration source of the scope.

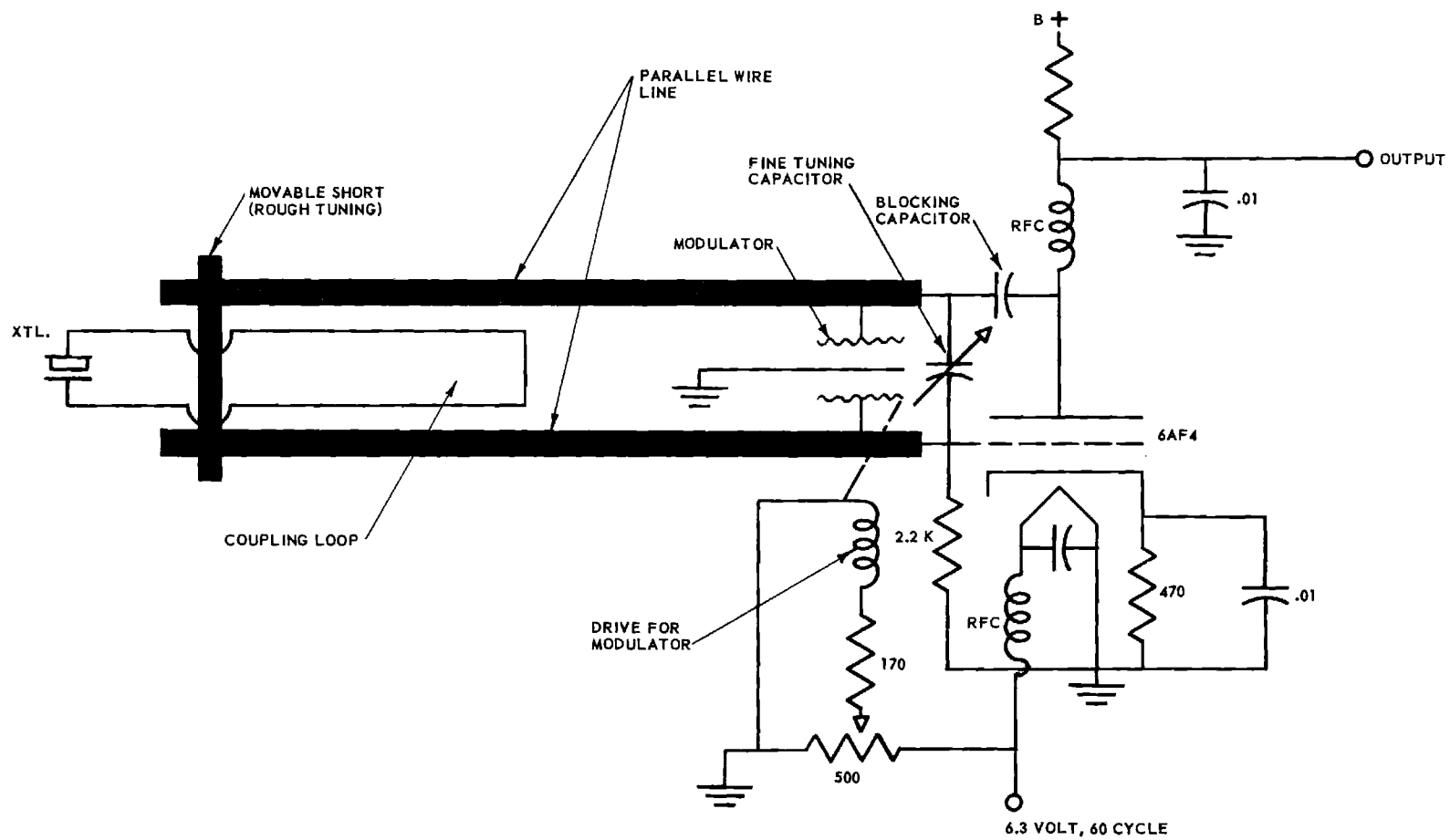


Figure 7.1. Frequency-Modulated Oscillator.

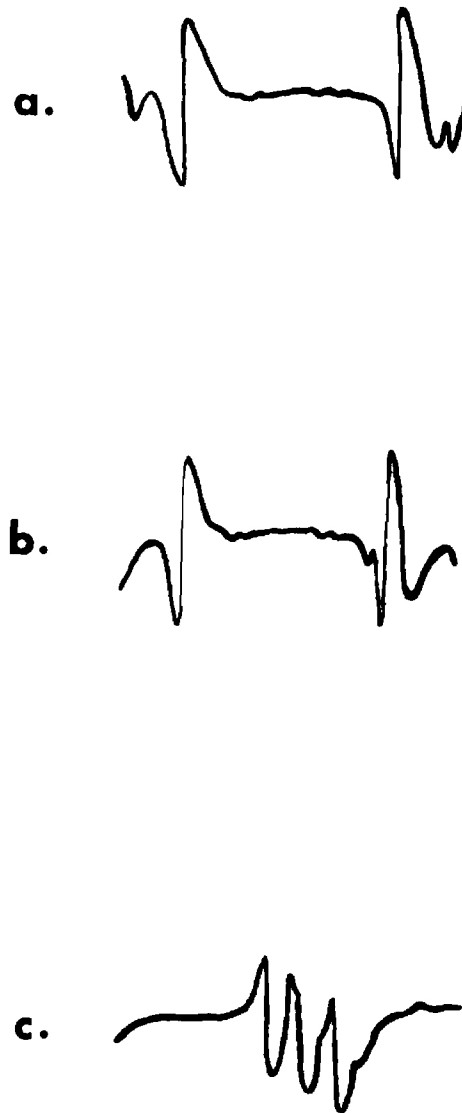


Figure 7.2. Crystal Overtone Responses.

The frequency of a response was measured by means of a TS-175/U frequency meter. This meter was tuned until its radiation caused a marker to be superimposed on the oscilloscope presentation of a crystal response. When the oscillator was radiating several frequencies, the marker and the crystal response appeared several times as the tuning capacitor of the oscillator was varied, but they remained superimposed only if they were of the same frequency.

The holder capacitance and the Q of the holder were measured at the same frequency for each of the above-mentioned crystals with the following results. Tables 7.1 and 7.2 summarize relevant data.

TABLE 7.1
FIXED PARAMETERS OF CRYSTALS TESTED

<u>Crystal</u>	<u>Holder Capacitance</u> (μmf)	<u>Holder Q</u>
B-5	4.8	138
B5.02	8.0	72
N6.Mc	11.5	81
B701	7.0	96
B9.148	9.0	81
B17.56	5.7	88
No. 43	9.7	128
No. 45	9.0	139
No. 84	9.0	165
No. 85	7.9	120

These tests demonstrated that quartz crystals could be successfully excited at frequencies much higher than those normally associated with such a resonator. However, it was evident that the magnitude of excitation was so small that the phenomenon might have no practical implication. Further consideration of the action, however, indicated that at least two possible applications of this high-order response might be established. One method applies to synchronization of oscillators and is discussed in a succeeding section, the other method applies to high-frequency discriminators and is discussed here.

TABLE 7.2
OVERTONE RESPONSES OF SEVERAL CRYSTALS

<u>Crystal Designation</u>	<u>Response Frequency</u> (Mc)	<u>Response Amplitude</u> (Millivolts)	<u>Nearest Integral Multiple of Fundamental</u>	<u>Remarks</u>
B-5 AR No. 5	247.3	50	49	Sharp well defined responses
	257.3	25	51	
	267.3	12	53	
	277.3	10	55	
	287.3	5	57	
	297.5	5	59	
B5.02 AR No. 3	245.7	100	49	Not as sharp as B-5
	255.7	50	51	
	265.7	25	53	
N6.Mc AR No. 1	223.1	29	37	
	235.0	22	39	
	242.3	24	Anomalous	
	246.9	22	41	
	259.0	4	43	
B7.01 AR No. 3	234.3	33	33	
	240.0	15	Anomalous	
	248.4	33	35	
	254.9	8	Anomalous	
	259.9	24	Anomalous	
	262.4	22	37	
	276.5	14	39	
B-9.148 AR No. 3	247.0	43	27	Very sharp responses
	265.1	24	29	
B17.56 28AA	240.1	28	14	
	275.1	16	16	
No. 43 25 Mc	274.0	43	11	
	325.3	12	13	
No. 45 25 Mc	274.0	50	11	
	325.0	12	13	
No. 84 36 Mc	261 approx.	50	7	All triple responses See Fig. 7.2 (C)
	329 approx.	25	9	
No. 85 36 Mc	261	50	7	
	329	25	9	

It was decided to investigate the possibility of adapting the method of afc to the present problem. One conventional afc system uses a discriminator having a d-c output voltage which is a function of the frequency applied to the input. The frequency-sensitive d-c output is used to control the frequency of the device supplying the signal to the discriminator. Therefore, a necessary condition for successful operation is that the frequency of the signal source be controllable by a suitably injected d-c voltage.

A circuit diagram of a conventional discriminator is given in Figure 7.3 A. For details of operation, see reference 6. As the frequency of the input departs from f_0 , the center frequency of the secondary tuned circuit, the output voltage varies as shown in Figure 7.3 B. Over the range from f_1 to f_2 , the output voltage is an almost linear function of impressed frequency, and it is this region over which control is possible, providing the signal generator is frequency-sensitive to applied d-c voltage.

In the circuit just discussed, the ability to control frequency is determined by the slope of the linear portion of the response curve, which is in turn determined by the Q of the secondary. If a crystal were substituted for the capacitance, as illustrated in Figure 7.4, and if the secondary were tuned so that the resonant frequency of the coil and crystal-holder capacitance coincided with the crystal resonance, it might be expected that the response of the discriminator would be extremely sharp because of the comparatively high Q of the crystal.

To test this possibility the circuit of Figure 7.4 was designed around a 5-mc crystal operating on its fundamental. The stage of amplification was necessary to raise the signal to a conveniently detectable level. A signal from an r-f generator was supplied to the input and the d-c output measured as a function of input frequency at several points in the neighborhood of 5 mc. The resulting plot is presented in Figure 7.5 and shows quite clearly that the crystal determines the slope of the response curve at the crystal resonance frequency. The existence of a small spurious response will be noticed at a frequency somewhat above the crystal fundamental. The slope of the steep portion of the curve is approximately 0.15 volt/kc.

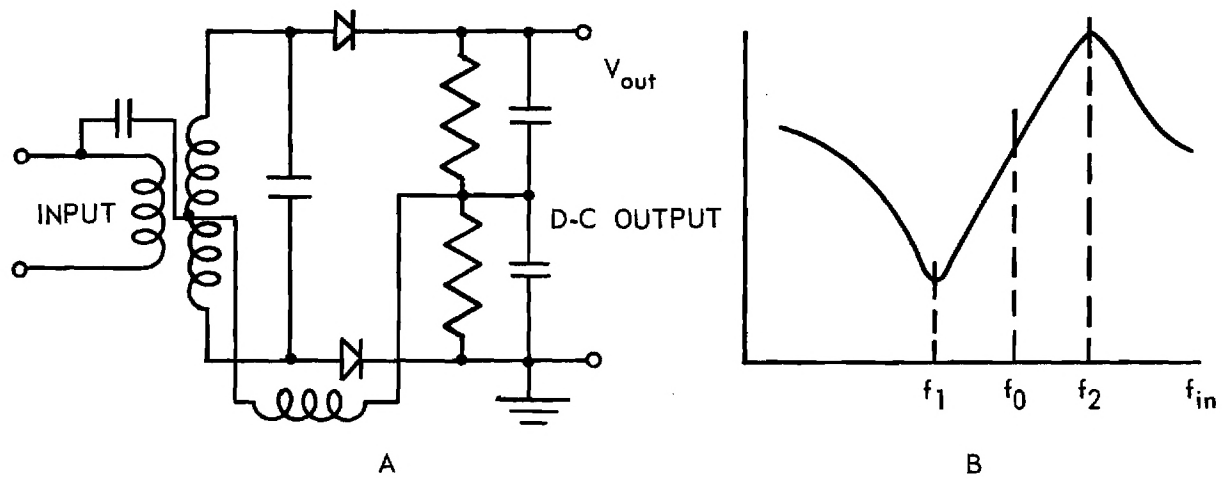


Figure 7.3. Conventional Discriminator Circuit and Response Curve.

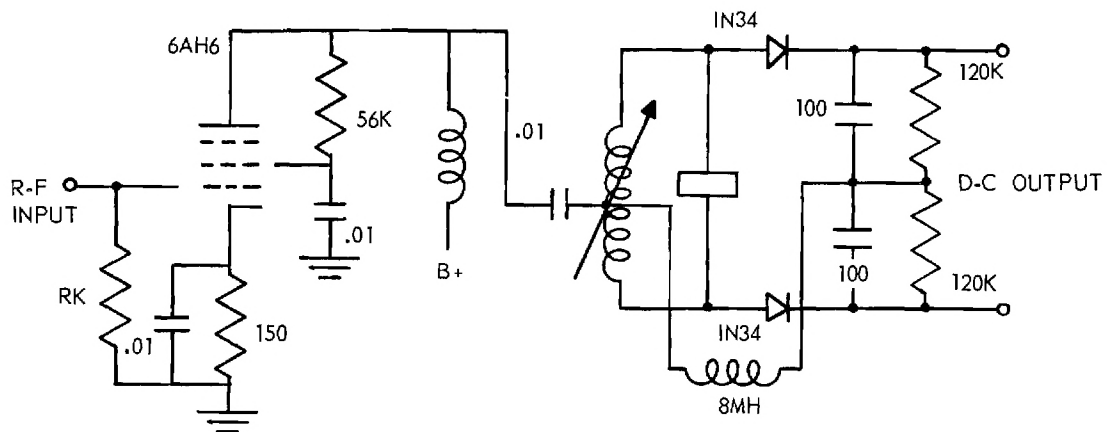


Figure 7.4. 5-Mc Amplifier and Crystal-Controlled Discriminator Circuit.

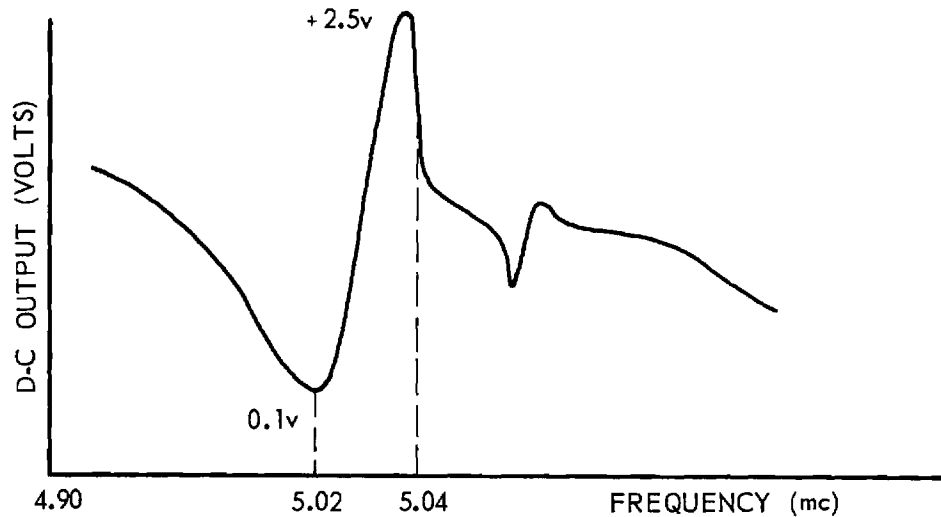


Figure 7.5. Response Curve of 5-Mc Crystal-Controlled Discriminator.

After the basic idea of the crystal-controlled discriminator had been proven to have some merit, it was decided to attempt to test the action at 25 mc, the fifth overtone of the crystal. Consequently, the circuit of Figure 7.4 was re-designed only to the extent of changing the transformer. When the response near 25 mc was measured, the plot of Figure 7.6 resulted. Very pronounced discriminator action was present, in fact, at each of several spurious response frequencies. These spurious responses are a property of the particular crystal being used and of the particular overtone and should not be considered as a basis for serious objection to the method.

It was decided next to run a test at 175 mc, the 35th overtone of the 5-mc crystal. At this frequency, great difficulty was encountered with the circuit of Figure 7.4, particularly with the transformer. The primary and secondary coils degenerated to portions of turns, and the problems of center tapping the secondary and getting the requisite coupling presented considerable difficulty. In fact, satisfactory results at this frequency were never obtained using transformer coupling. A redesign was carried out by Mr. J. C. Sellers, and the circuit of Figure 7.7 was constructed by him. The three stages of amplification shown were found to be desirable, and the particular form of the stages was

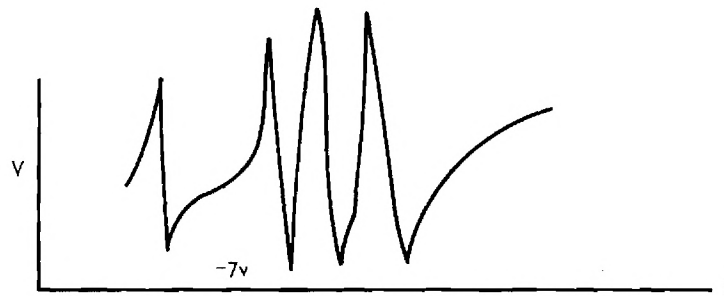


Figure 7.6. Response Curve of 25-Mc Crystal-Controlled Discriminator.

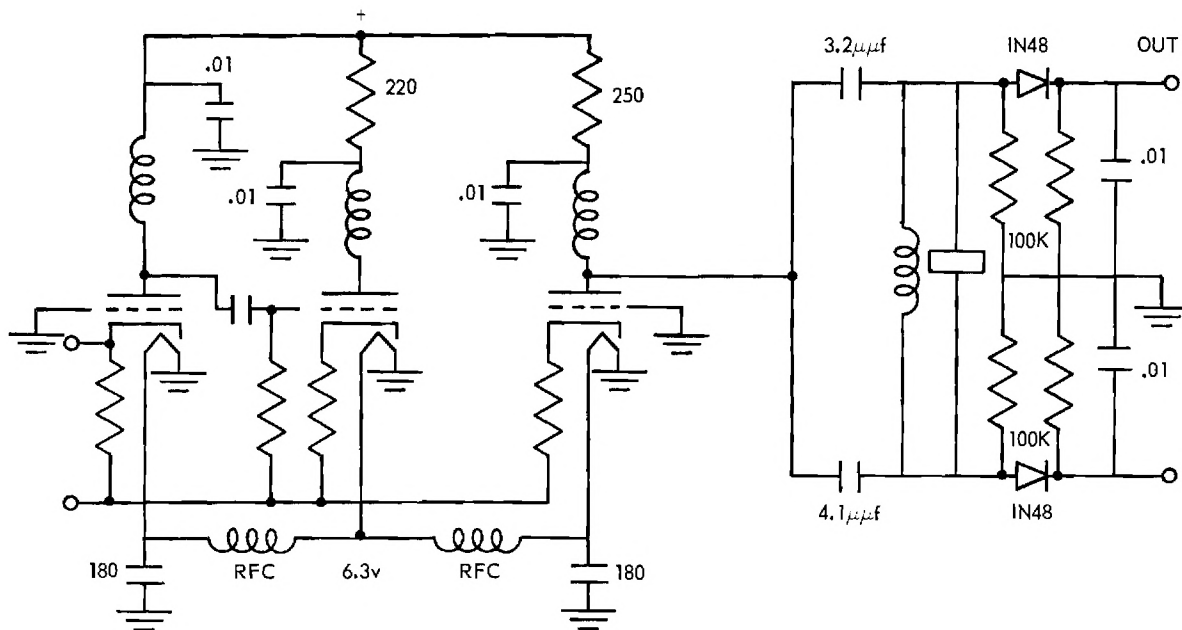


Figure 7.7. Amplifier and Direct-Coupled Discriminator Circuit.

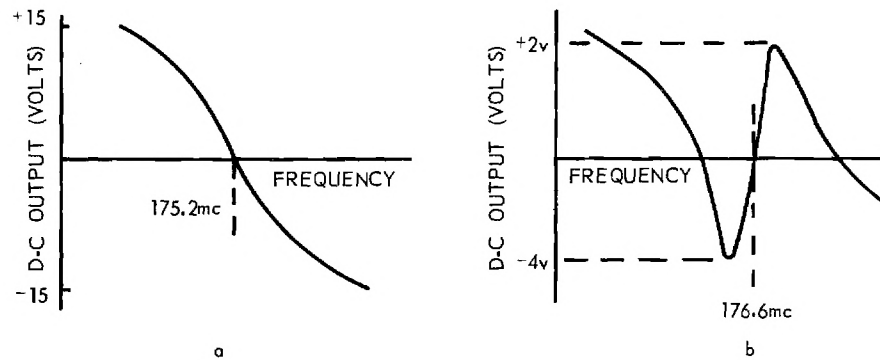


Figure 7.8. Direct-Coupled Discriminator Response Curve Near 175 Mc.

largely determined from impedance considerations, the circuit being designed to operate from a Hewlett-Packard signal generator with an output impedance of 50 ohms. The coil of the discriminator was tuned, by a spreading of the turns so that the resonant frequency of the coil and the crystal-holder capacitance coincided with the overtone response frequency of the crystal.

The direct-coupled discriminator response was investigated first with a capacitor in place of the crystal. The capacitance was chosen to be equal to that of the crystal holder. A plot of the response curve of this experimental arrangement is presented in Figure 7.8 A. Next the crystal was inserted as shown in Figure 7.7 and another run taken. This yielded the plot of Figure 7.8 B.

The shift in frequency for corresponding points of A and B is due to the fact that the dummy capacitance used for A was not exactly equal to the crystal-holder capacitance, while the fact that the crystal response is not exactly symmetrical about the d-c-voltage-equals-zero axis may be accounted for by the lack of exactness in tuning the discriminator coil to the crystal overtone frequency.

A later test with a slightly revised circuit demonstrated that a sharper discriminating action can be achieved. The only actual change in the circuit was the substitution of a variable capacitor in place of one of the 3.2 μf fixed capacitors shown in one series branch of Figure 7.7. A more nearly optimum initial balance of the circuit was achieved. The resultant curves of d-c voltage, with and without crystal, are shown in Figure 7.9.

Inspection of this figure shows that very sharp discriminatory action is possible by means of a piezoelectric quartz crystal. The magnitude of voltage change may also be sufficient to produce satisfactory afc action. However, a present weakness of this form of control lies in state of development of reactance-tube circuits by which to control UHF or even VHF oscillators adequately. At frequencies below 100 mc, the relatively conventional pentode reactance tube performs quite satisfactorily, but at higher frequencies other forms of control devices are required.

C. Types of Reactance-Tube Circuits

In applying reactance tube action to VHF and UHF oscillators, care must first be exercised in the selection of the proper type tube for the reactance agent, since the interelectrode capacitance of nonminiature type vacuum tubes will immediately disqualify their use. For this reason, a common-grid type reactance circuit, using a miniature-type tube, was selected.

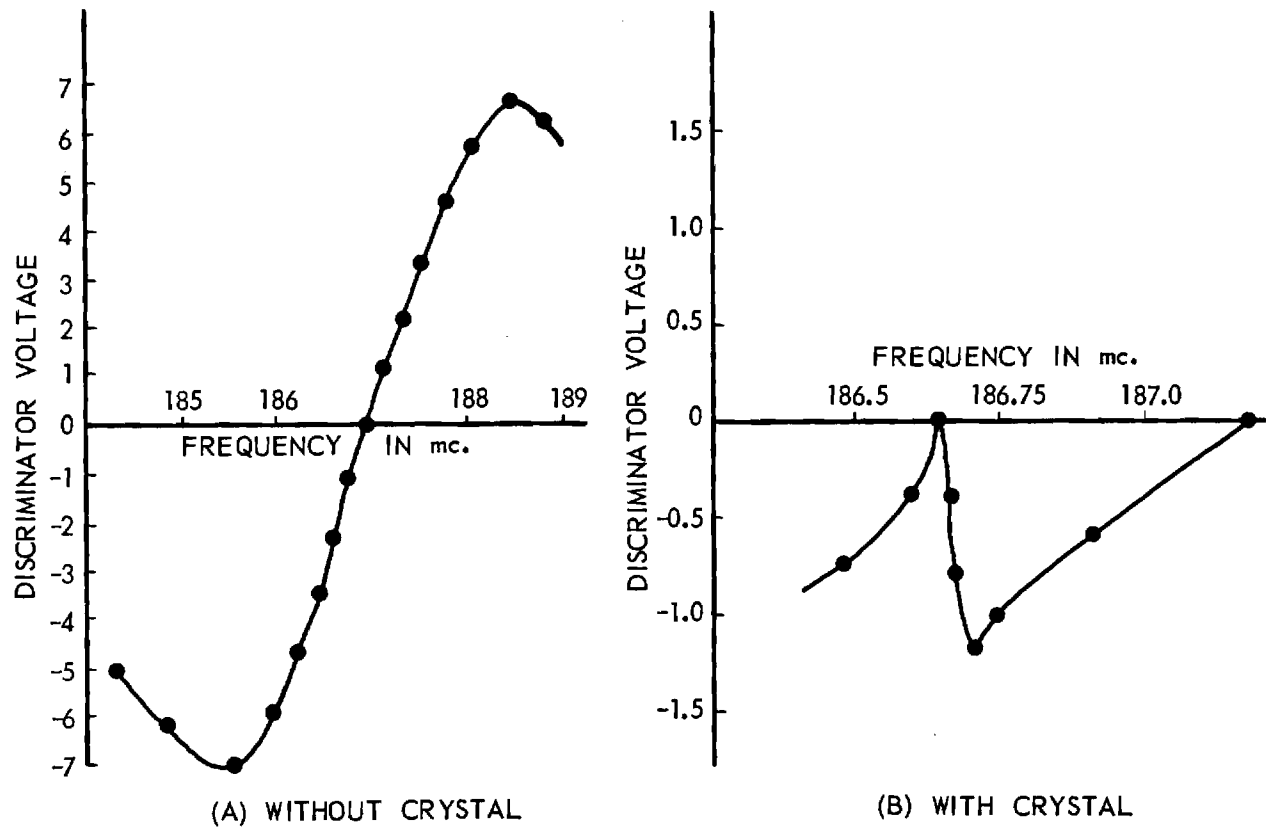


Figure 7.9. Discriminator Curves.

Observation of the governing features of this type circuit will help to give a composite picture of the minimum requirements necessary to produce reactance action. The basic circuit of a common-grid reactance tube is shown in Figure

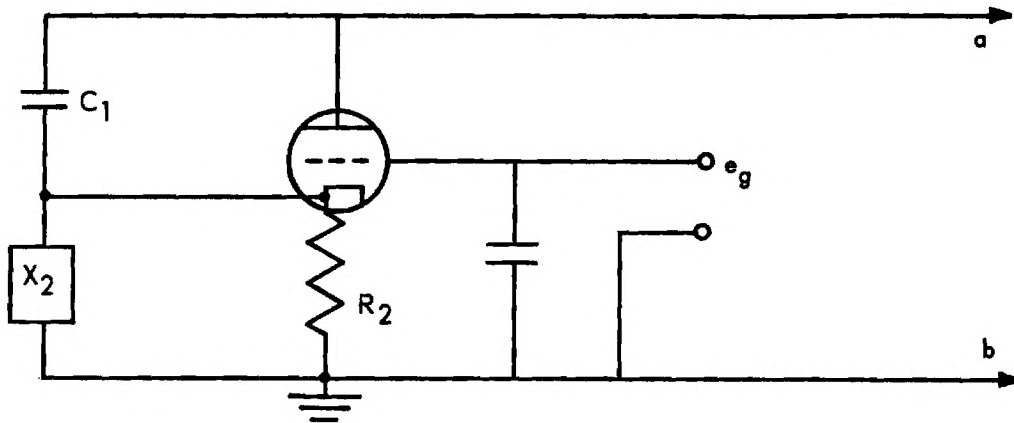


Figure 7.10. Common-Grid Reactance Tube Circuit.

7.10. It can be shown (7) that circuit conditions can be adjusted so that equivalent parallel reactance and resistive components between terminals ab are

$$X_{ab} \doteq X_1 (1 + R_2 G_m)$$

and

$$R_{ab} = \mu R_2$$

so that the oscillator tank circuit is in parallel with a capacitance, C' :

$$C' = \frac{C_1}{1 + R_2 G_m}.$$

The reactive component depends upon the mutual conductance of the tube and can be made a function of bias and discrimination (modulation) voltages applied to the grid circuit. If the amplification factor of the tube remains constant, the resistance component is independent of tube operating conditions, and loading on the oscillator is uniform.

The difficulty of obtaining a precise knowledge of component values at VHF and UHF makes circuit equations difficult to apply to circuit design. In order

to achieve peak or proper circuit performance, it was necessary to make changes and adjustments under operating conditions.

Using a type 6AF4 miniature triode, it was necessary to change the basic common-grid design to the configuration shown in Figure 7.11.

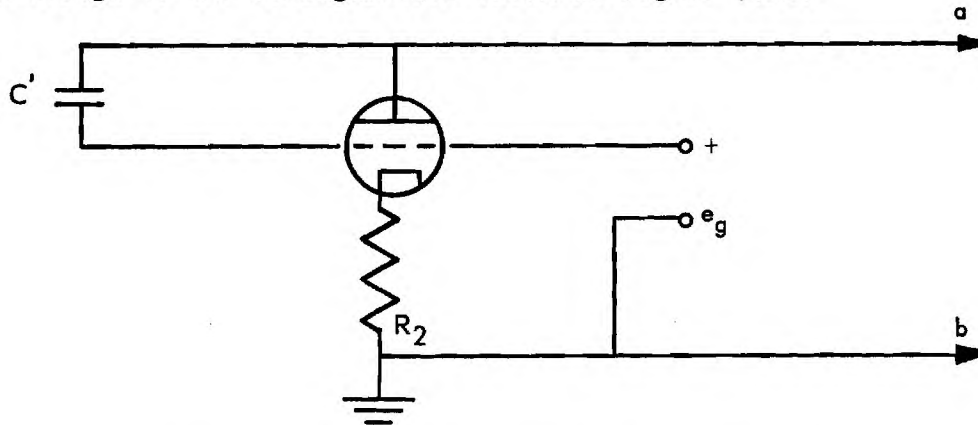


Figure 7.11. Modified Common-Grid Circuit.

Applying circuit theory, it was found that the equivalent parallel capacitance between terminals ab was $C' = C_1 R_2 G_m$, where R_2 = the total resistance in the grid-cathode circuit. When a bias or modulating voltage is impressed across the terminals of the grid circuit, it will vary the grid voltage of the tube and clearly vary G_m . A variation in mutual conductance will change the effective capacitance, C' .

The common-grid circuit performs satisfactorily at frequencies not greatly exceeding 100 mc but at higher frequencies tend to degrade the performance of the oscillator which it shunts. This effect is due to the relatively low output impedance of conventional high-frequency triodes. This low impedance tends to lower the frequency of the oscillator and to reduce the Q of its tank circuit. Hence, a common-grid reactance tube is limited in application unless the undesired shunting effect is reduced.

Operation at high frequencies with lighthouse tubes as oscillator and reactance tube has been achieved by other experimenters (5) but the equipment arrangement requires two separate cavities and is both relatively massive and complicated. Another reactance tube-oscillator combination which may employ conventional triodes involves a quite different arrangement.

The reactance-tube oscillator was constructed utilizing the circuit and principles described in reference 8. A schematic diagram of this circuit is shown in Figure 7.12.

The principle of operation is self-evident from the schematic diagram. The oscillator tube is on the left. Its grid and plate are connected between the two ends of the terminated half-wave length cable which is of 100 ohms characteristic impedance in this experimental model. The cable was actually terminated in 200 ohms, because the oscillator failed to operate with 100 ohms.

The plate of the reactance tube is connected to the plate of the oscillator, and the grid is moved along a tap connection on the line. In this way, one obtains a point corresponding to a position which is a quarter wavelength from the plate end of the line. Under these conditions, the reactance tube is driven by a signal which is 90 degrees lagging that of the plate. Thus, the reactance tube appears as an inductance shunted across the oscillator, since it draws quadrature current.

If the transconductance of the reactance tube is varied, the amount of quadrature current and, thus, the inductance is varied. This is conveniently done by varying the grid bias on the reactance tube.

The completed assembly showing the half-wave length line and the associated circuitry is shown in the accompanying photograph, Figure 7.13. The line was constructed from two pieces of quarter-inch-thick-brass. Each piece was grooved with a ball mill of 3/16-inch diameter to a depth of 3/32 inch. The construction is seen from Figure 7.14, in which the pieces are shown disassembled. The inner conductor was made by stripping the outer conductor from a length of 93-ohm RG 62/U cable. The insulation was taken off the inner conductor in the region of the slotted portion to provide a grid-connecting point.

Tests were run by varying the bias on the reactance tube from minus 1.6 to minus 15 volts. Table 7.3 shows the results.

Except for the disturbingly low output voltage, the results were reasonably satisfactory. A change of approximately five per cent in frequency due to d-c applied to the reactance tube should give reasonable control of the system.

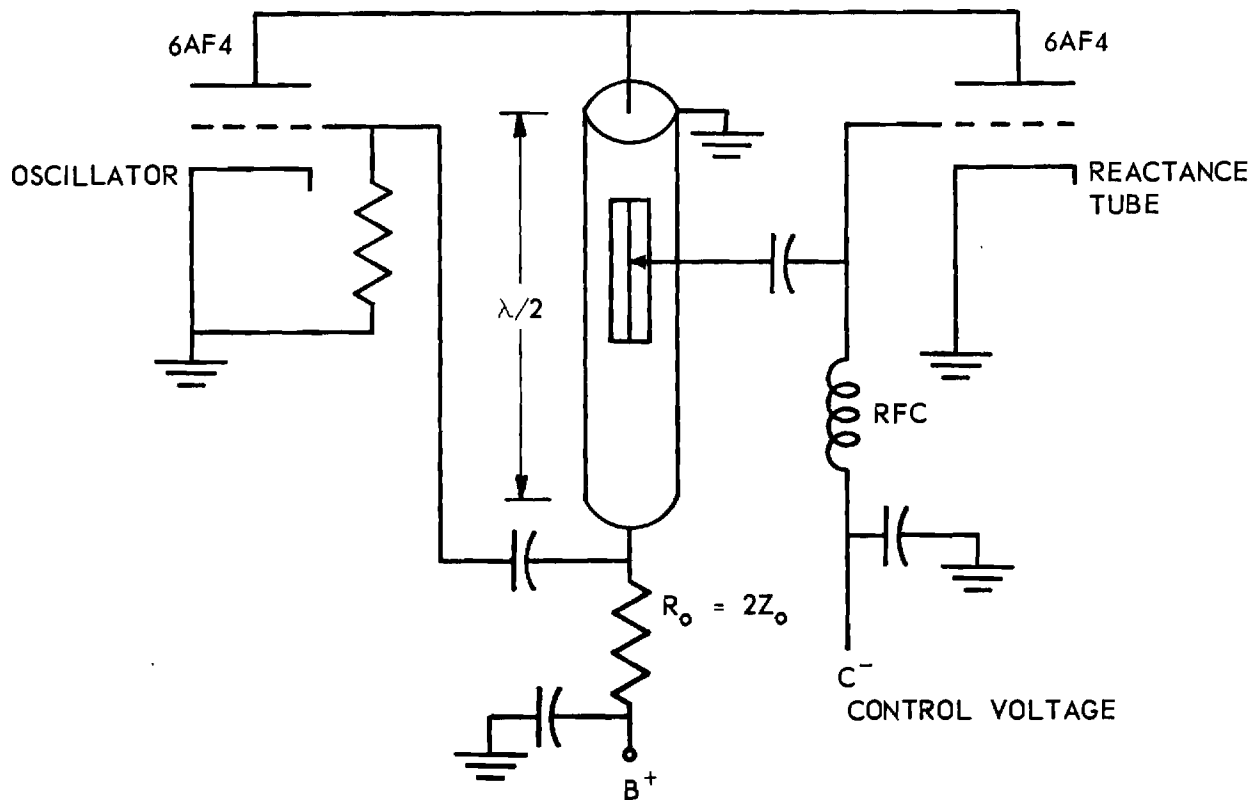


Figure 7.12 Reactance-Tube Oscillator Schematic.

Although it has not as yet been attempted, this arrangement may provide control at frequencies as high as 400 mc. If so, by a tripling process the system could be used to control an oscillator in the 1200-mc region.

D. High-Frequency Control Through Synchronization of Oscillators

If a reference signal of suitable amplitude and frequency is injected into an appropriate section of a free-running oscillator, the frequency of the oscillator may be pulled to that of the reference source. Under certain conditions the phase of the oscillator voltage may become synchronized to that of the reference so that their relative phase remains constant. In this case, the oscillator is locked to the reference source and a true synchronization or locking phenomenon is said to exist.

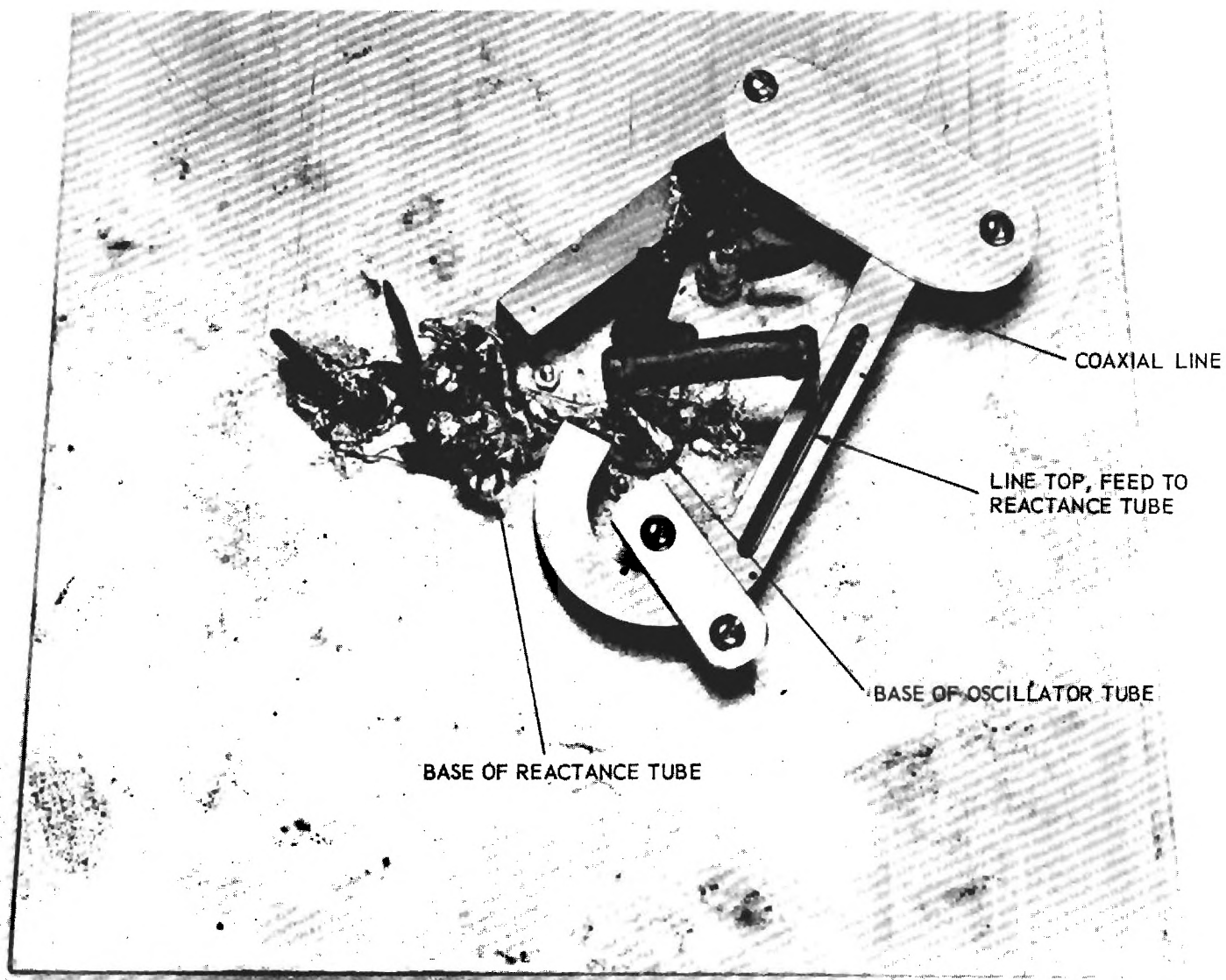


Figure 7.13. Photograph of Assembled Reactance-Tube System.

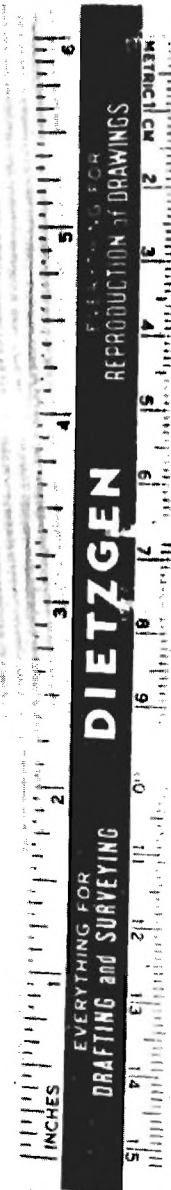
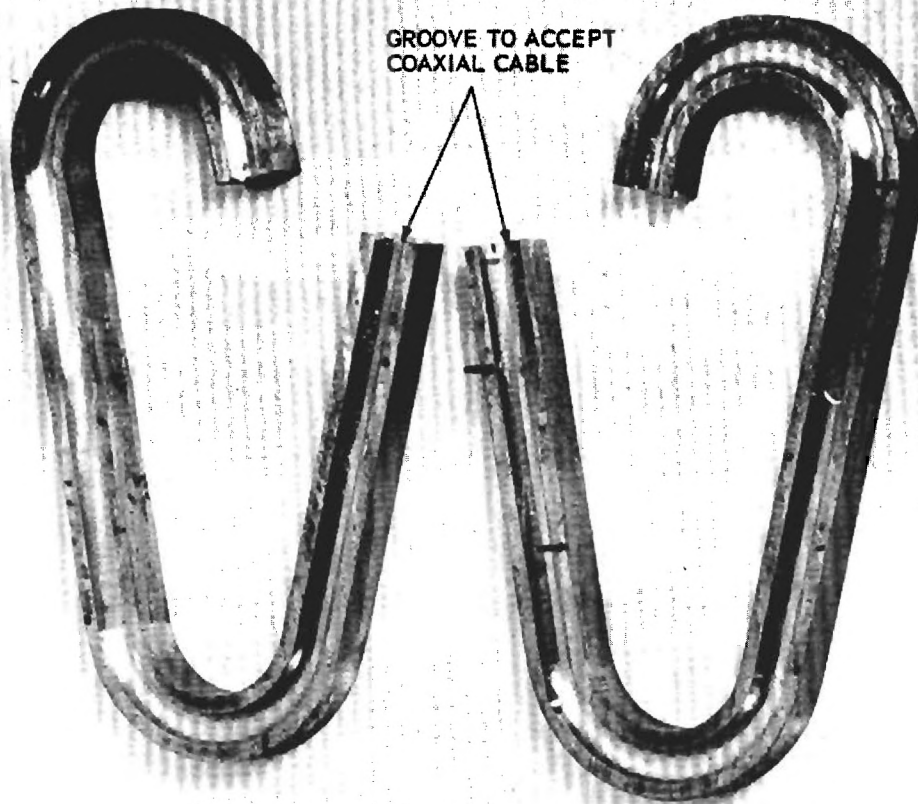


Figure 7.14. View of Disassembled Line.

TABLE 7.3
REACTANCE TUBE FREQUENCY VARIATIONS

<u>Reactance Grid</u>	<u>Plate Volts</u>	<u>Total Current</u> (ma)	<u>Output</u>	<u>Frequency</u> (mc)
15	100	27	3.7	188.36
10	100	28	3.8	188.64
9	100	28	3.8	188.70
8	100	29	3.9	189.40
7	100	30	3.9	189.98
6	100	32	4.4	191.264
5	100	35	4.8	192.86
4	100	38	5.3	194.90
3	100	40	5.7	197.10
2	100	42	6.0	199.40
1.6	100	43	6.0	201.58

Synchronization is of importance in many commercial applications. It is usefully employed in f-m receivers and limiters, in television, aid-to-navigation, etc. In the field of frequency control, it assumes importance because of one fundamental characteristic, this being that the synchronized oscillator assumes the stability of its synchronizing source. The significance of this statement is illustrated by the effect of synchronization upon an LC oscillator of inherently poor frequency stability when the synchronizing source is the output of a highly stable, crystal-controlled oscillator. Improvements in stability of several orders of magnitude may be effected in such a case.

The capabilities of an oscillator of being synchronized are best specified in terms of a band of frequencies which extend either side of the free-running frequency. This band is termed the "band of synchronization" and is a quantity which is directly proportional to the strength of the synchronizing voltage and inversely proportional to the Q of the tank circuit in an LC oscillator. It is logical that an oscillator with a wide band of synchronization should be a convenient vehicle for the locking phenomenon and conversely for that with a narrow band. It is evident, for example, that in the case of a wide band, the synchronizing source may vary considerably in frequency without falling outside the band and, hence, without causing loss of synchronization.

1. Bandwidths and Synchronization by C-W Signals

In an important paper, Adler (9) has developed a relatively simple theory by which to determine the bandwidth of synchronization in any specific LC oscillator. His analysis relates anode voltage, grid voltage, and externally injected voltage in a synchronized oscillator and may be most easily understood by reference to Figure 7.15. The quantities symbolized by vectors are defined as

V_1 = externally injected signal of frequency ω_1 ,

V_R = voltage returned from tuned circuit, and

V_g = voltage at grid of tube of frequency ω .

The conditions defining the bandwidth of synchronization are obtained by considering Figure 7.15 B as a closed triangle. The triangle is closed when $d\alpha/dt = 0$, which is to say that $\omega = \omega_1$, of that synchronization exists.

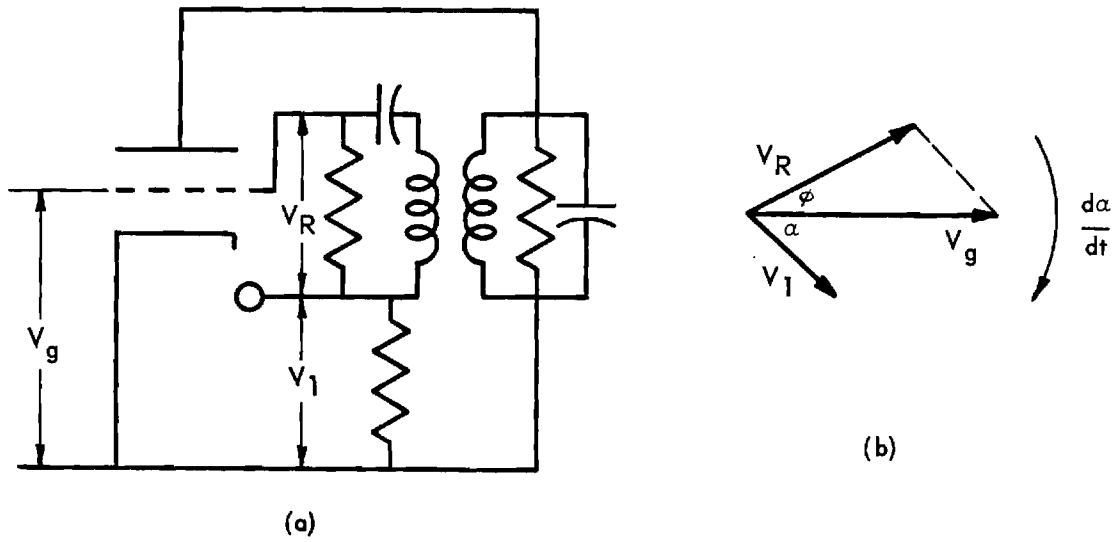


Figure 7.15. Relationships in a Synchronized Oscillator.

It is evident that the grid voltage V_g is the vector sum of V_1 and V_R , and further that the phase ϕ must be due to the tuned circuit. It is known that in a simple tuned circuit, for small deviation of frequency

$$\phi \doteq \frac{2Q}{\omega_0} (\omega - \omega_0) \quad (7.1)$$

where ω_0 is the angular frequency of circuit resonance.

It is also evident from Figure 7.15 B that, for small ϕ

$$\phi \doteq \tan^{-1} \frac{V_1 \sin \alpha}{V_g} \doteq \frac{V_1 \sin \alpha}{V_g} \quad (7.2)$$

Equating equations 7.1 and 7.2, one obtains the important relationship

$$\omega - \omega_0 = \frac{\omega_0}{2Q} \frac{V_1}{V_g} \sin \alpha \quad (7.3)$$

from which the one half bandwidth is obtained by observing that the maximum

value of α may be expected to attain, and still have synchronization maintained, is 90 degrees. For this value of α , the one-half bandwidth is given by

$$\omega_c - \omega_o = \frac{\omega_o}{2Q} \frac{V_1}{V_g} \quad (7.4)$$

where ω_c is the angular frequency at the edge of the band.

It is evident from equation 7.4 that the bandwidth is directly proportional to the amplitude of injected voltage but is inversely proportional to both the amplitude of grid voltage and to the Q of the tank circuit. If the oscillator is to be easily synchronized, it is necessary that the Q be low and that the grid drive be small. These are the usual characteristics of an oscillator of poor stability. So it may be correctly concluded that unstable oscillators are in most cases, relatively easy to synchronize while stable oscillators are difficult to synchronize.

The synchronizing process may be usefully employed in frequency multiplication; the process sometimes being described as a "pulling into phase" of every second or third cycle of the synchronized oscillator by the injected voltage and sometimes as the direct effect of the second or third harmonic of the input. In any case, the magnitude of input voltage required for synchronization is much greater for doubling or tripling than for synchronizing at the fundamental frequency.

The order of magnitude of synchronizing voltage required in UHF oscillators is illustrated by a series of tests conducted recently on this activity. The arrangement is illustrated in Figure 7.16.

The oscillator utilizes a hairpin loop and is tuned by the small variable capacitor C_1 which terminates the loop. By selection of each several loops, the oscillator was operated at various frequencies within the region of 300 to 850 mc. The resistor R_1 , shown shunting the plate-to-grid load, was introduced for the purpose of deliberately degrading the Q of the oscillator tank, thereby increasing the bandwidth of synchronization and improving the tendency toward establishing a "lock" with the injected signal.

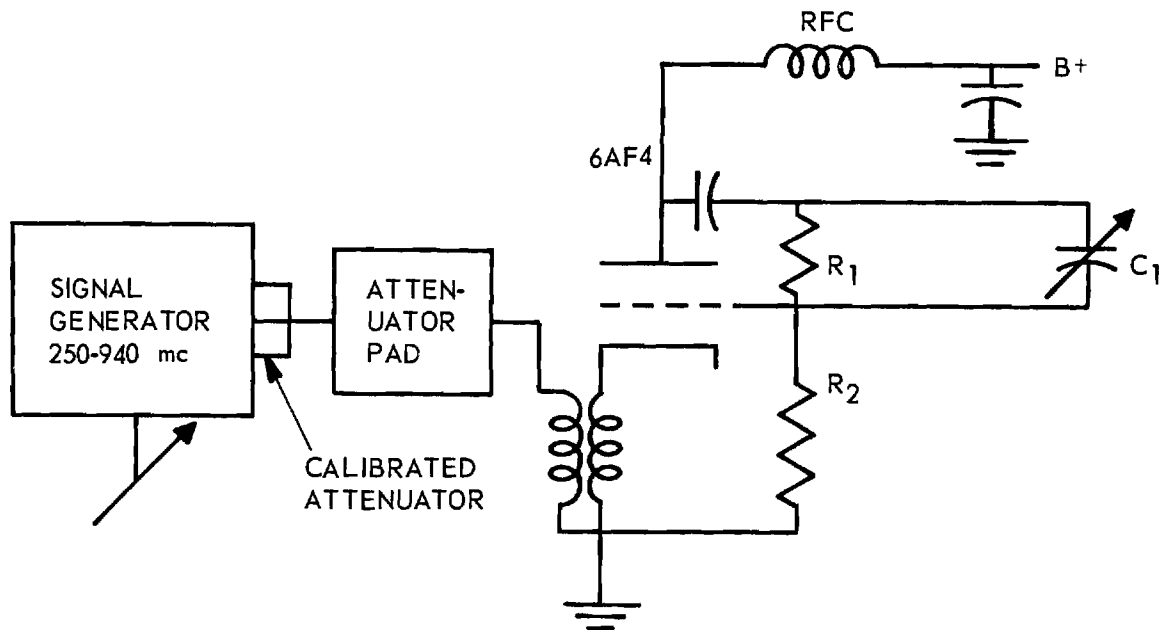


Figure 7.16. Circuit Arrangement for Synchronization Tests.

No difficulty was experienced in synchronizing the oscillator with a small signal from the generator when the frequency ratio was 1:1. Synchronization was possible, but less easily accomplished when the frequency ratio was 1:2 (i.e., doubling) and still less easily accomplished when the ratio was 1:3. The results are best described in tabular form. Table 7.4 shows the results of tests conducted in the frequency range under discussion. The following definitions apply:

f_o = free-running frequency of oscillator,

V_1 = amplitude of injected voltage,

f_1 = center frequency of injected voltage, and

$2f_c$ = width of band over which synchronization occurred.

TABLE 7.4
BANDS OF SYNCHRONIZATION

(a)		(b)		(c)		(d)	
$f_o = 336 \text{ mc}$		$f_o = 795$		$f_o = 795$		$f_o = 795$	
$f_1 = 336 \text{ mc}$		$f_1 = 795$		$f_1 = 397.5$		$f_1 = 265$	
V_1	$2f_c$	V_1	$2f_c$	V_1	$2f_c$	V_1	$2f_c$
(mv)	(kc)	(mv)	(mc)	(mv)	(mc)	(mv)	(mc)
50	64	200	1.10	500	2.0	500	0.2
100	144	300	1.5	1000	3.5	1500	1.10
200	352	500	5.5	1500	5.0	2000	1.2
500	832						

2. Synchronization with Interrupted Wave Trains

Thus far the assumption has been implied, if not explicitly expressed, that the synchronizing signal is a continuous function of time and of amplitude that is essentially constant. On the basis of conjecture, it would not seem improbable that synchronization, or near-synchronization, could still exist in an oscillator if a few cycles of the injected voltage were lost because of some form of interruption. One would anticipate that during the "off" time of the synchronizing voltage that the oscillator previously locked at the synchronizing frequency f_1 , would tend in a transitory manner toward its free-running frequency f_o . However, if the interruption was of sufficiently small-time duration, the reapplied locking signal would quickly return the frequency to f_1 . If the period of interruption were sufficiently short, the small transients would be essentially negligible, and one could still refer to the oscillator as "locked".

It can be quickly verified experimentally that such synchronization (or quasi-synchronization) can and does exist, and under far more general circumstances than the preceding paragraph would imply. If a signal source is

modulated by a rectangular wave, so that the output consists of a time period during which a sinusoidal voltage of amplitude V_1 and frequency f_1 is present, and another equal time period during which no voltage is present, it may be demonstrated that such a signal will synchronize a free-running oscillator. In fact, the frequency of that oscillator becomes exactly f_1 , as may be proved by frequency counters and/or Lissajou patterns. A further surprising observation is that the "on" time of the synchronizing source can be considerably less than the "off" time and synchronization will still exist.

One method of explaining the phenomenon is to represent the interrupted wave train by its equivalent Fourier series. Consider the representation of a periodic pulse of unit amplitude shown in Figure 7.17.

In the usual method (for example, see Cuccia 10) of the complex representation of a Fourier series, the coefficients of individual terms of the

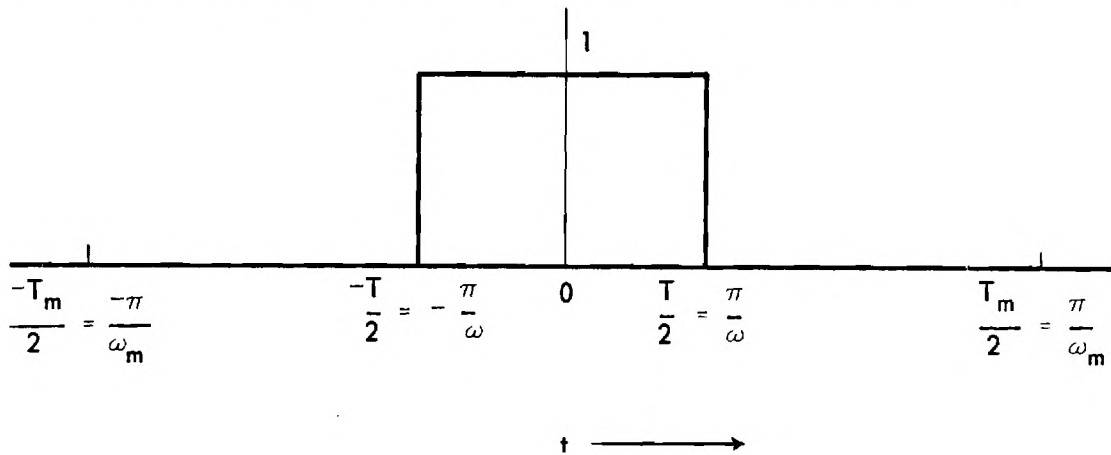


Figure 7.17. Representation of Periodic Pulse.

series are given by

$$C_n = \frac{\omega_m}{2\pi} \int_{-\pi/\omega}^{\pi/\omega} e^{-jn\omega_m t} dt, \quad (7.5)$$

whence

$$C_n = \frac{\omega_m}{-j2\pi n\omega_m} \left[e^{-j(n\omega_m \pi/\omega)} - e^{j(n\omega_m \pi/\omega)} \right] = \frac{1}{n\pi} \sin nk\pi, \quad (7.6)$$

where $k = T/T_m = \text{duty cycle}$.

The total expression for the pulse may now be written as

$$f(t) = \frac{E}{\pi} \sum_{n=-\infty}^{\infty} \frac{\sin nk\pi}{n} e^{jn\omega_m t}. \quad (7.7)$$

Since $\sin nk\pi$ goes to zero for integral values of the quantity nk , the harmonic component whose number n is equal to $1/k$ or multiples thereof will be of zero amplitude. For example, if the pulse is a square wave, where $k = 1/2$, even-numbered components are of zero amplitude.

The spectrum of a sine wave of amplitude E and of angular frequency ω_0 , which is amplitude-modulated by a rectangular pulse, can now be visualized. The wave, modulated by a rectangular wave of repetition frequency ω_m , and a portion of its spectrum are illustrated in Figure 7.18. The effect of change of duty cycle is shown.

A practical aspect considered to be of considerable importance is the fact that several potential synchronizing signals are available from one original c-w signal. If the duty cycle is small, there exist several sidebands $(\omega_0 \pm n\omega_m)$ of amplitude not significantly less than that of the carrier amplitude.

An experiment recently conducted on this project will serve to illustrate the phenomenon. The equipment arrangement is shown in Figure 7.19.

The free-running oscillator was operated at a nominal frequency of 5 mc. The amplitude of input signal was first adjusted so that the band of synchronization was about 50 kc. The frequency of the signal generator was then varied over the band of synchronization. The synchronized oscillator followed smoothly, exhibiting the same stability as that of the signal generator. The envelope of oscillations showed a small amount of 100-kc amplitude modulation.

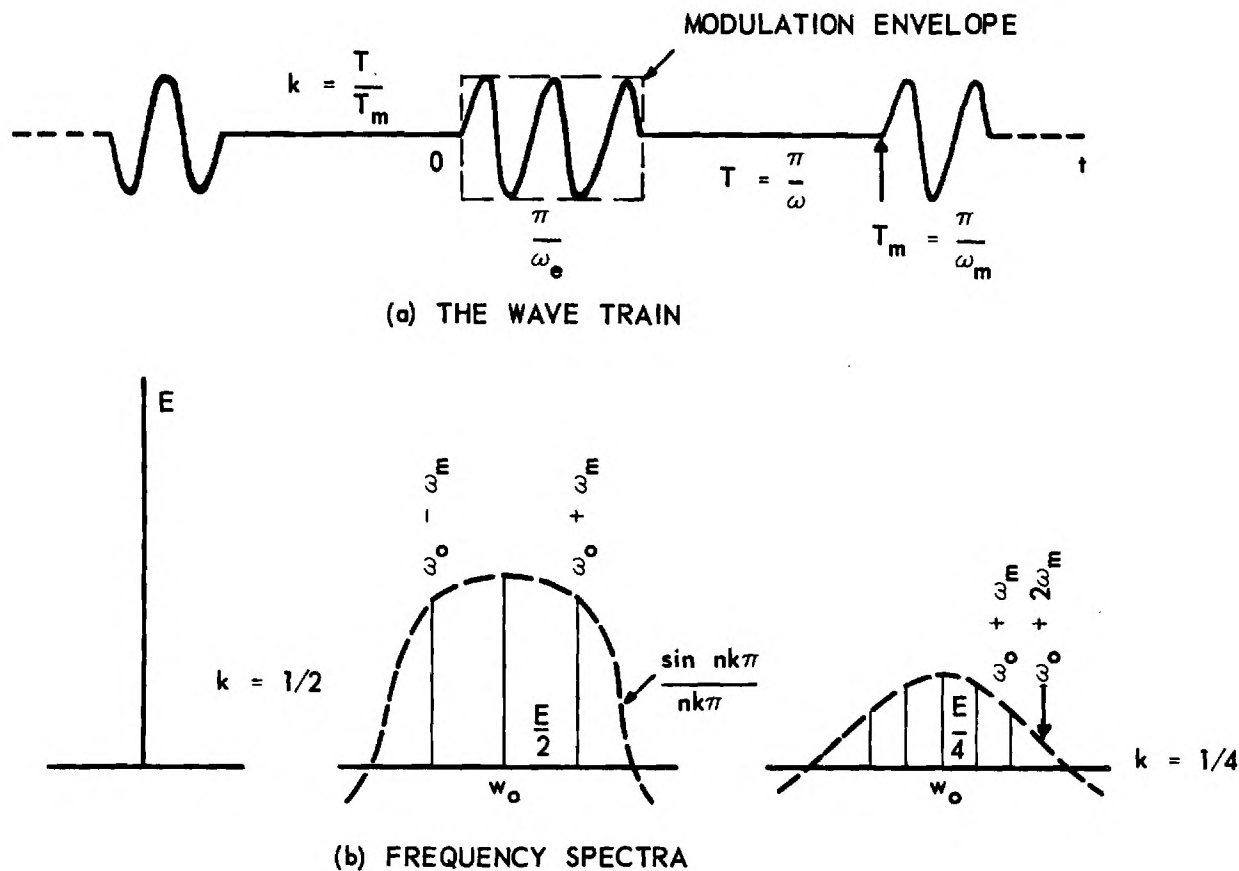


Figure 7.18. Spectra of Pulse-Amplitude-Modulated Wave as Function of Duty Cycle.

The synchronizing action can best be demonstrated by tuning the tank circuit of the free-running oscillator in amounts sufficient to cover the entire frequency spectrum illustrated symbolically in Figure 7.18 B. If proper action occurs, the oscillator should change frequency in a series of "jumps" rather than continuously as its center frequency falls successively inside the "band of synchronization" associated with each of the significant sidebands. In the test illustrated in Figure 7.19, the signal generator, rather than the oscillator, was varied in frequency. The action that occurred is best illustrated by reference to Figure 7.20, in which f represents the frequency of the "oscillator to be synchronized" and f_1 represents the frequency of the signal generator.

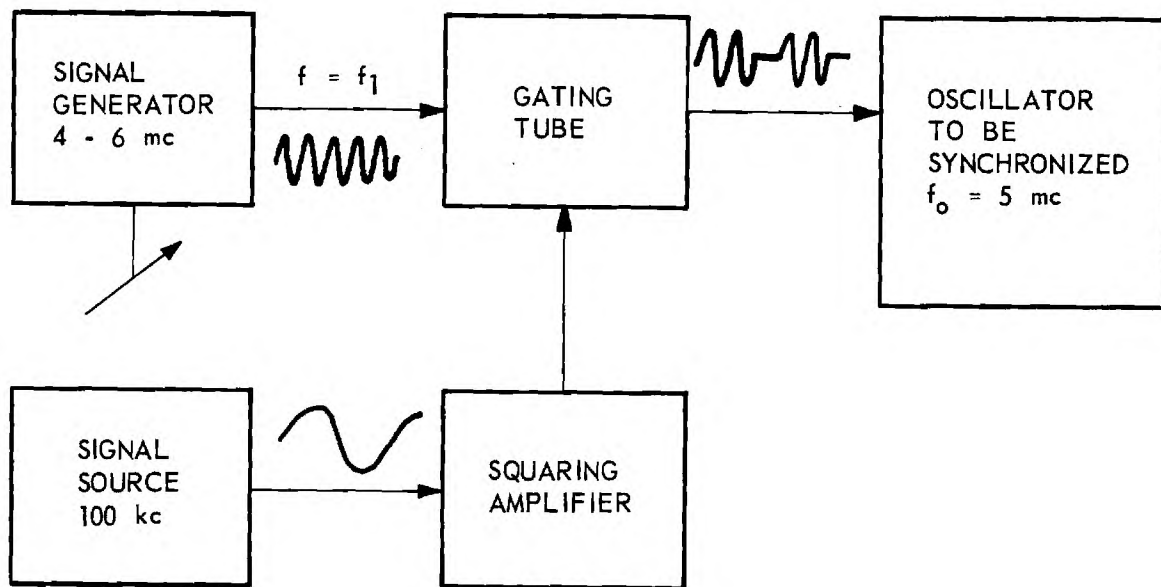


Figure 7.19. Equipment Arrangement for Synchronization by Interrupted Wave Trains.

The figure illustrates the synchronizing action of the carrier and its upper sidebands. The action for the lower sidebands and carrier is a mirror image of that shown. The action is explained as follows: when the signal generator frequency f_1 is moved back and forth through f_o , the actual frequency of the oscillator follows in a 1:1 relationship, resulting in a straight plot. As the frequency f_1 is increased to the point marked A, synchronization is lost and the oscillator returns to its frequency f_o . However, if f_1 is further increased, there is a point B at which synchronization is abruptly gained once more. At point C synchronization exists, the signal generator injecting a signal of 5.1 mc, the oscillator running at 5.1 mc minus 100 kc (f_m) that is, at 5.0 mc. The same action is illustrated as f_1 is further increased, bands of synchronization being evident centered at the frequencies $f_o + 2f_m$ and $f_o + 3f_m$. It is of interest to note that, in theory, the amplitude of input at the frequency $f_o + 2f_m$ should be zero, since the modulating signal is a square-wave (i.e., $k = 1/2$). In practice, enough non-symmetry exists to result in some output at the frequency of the second sidebands.

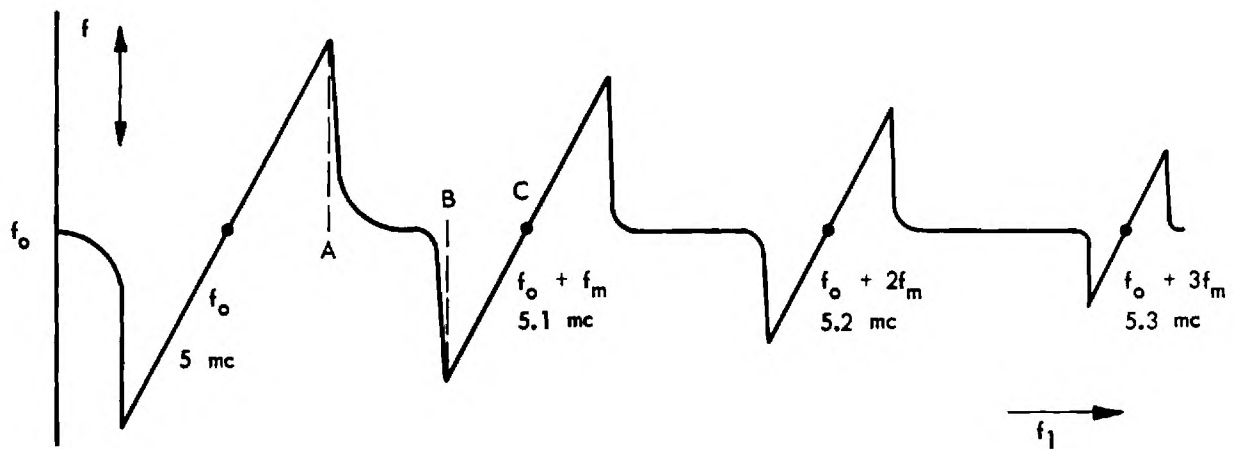


Figure 7.20. Synchronizing Action of Interrupted Wave Train.

The band of synchronization corresponding to each sideband of the input signal is found to be proportional to the amplitude of that sideband. This fact leads to the interesting possibility that a tunable UHF free-running oscillator might be synchronized, in steps, to any one of a very large number of discrete frequencies existing in the spectrum of a single input signal. If the frequencies in the spectrum are stable, then the discrete frequencies of the synchronized oscillator will also be stable. A possible method of producing a spectrum of stable frequencies is to interrupt, at a rate determined by a low-frequency crystal-controlled oscillator, the output of a high-frequency crystal-controlled oscillator. Another method is to control the self-blocking rate of a high-frequency free-running oscillator by means of a low-frequency crystal-controlled input.

Uniform synchronization action may be expected to result from inputs which have the same amplitude. This implies that if step-tuning and step-locking are desired at uniformly spaced frequencies, then the input signal should desirably have a spectrum which is "flat" over the frequency range of interest.

It has been shown (11) that a spectrum can be generated whose envelope closely approximates a rectangle. In general, the generating waveform is periodically repeated and in the form of Figure 7.21 A and its spectrum is in the form of part B of the same figure.

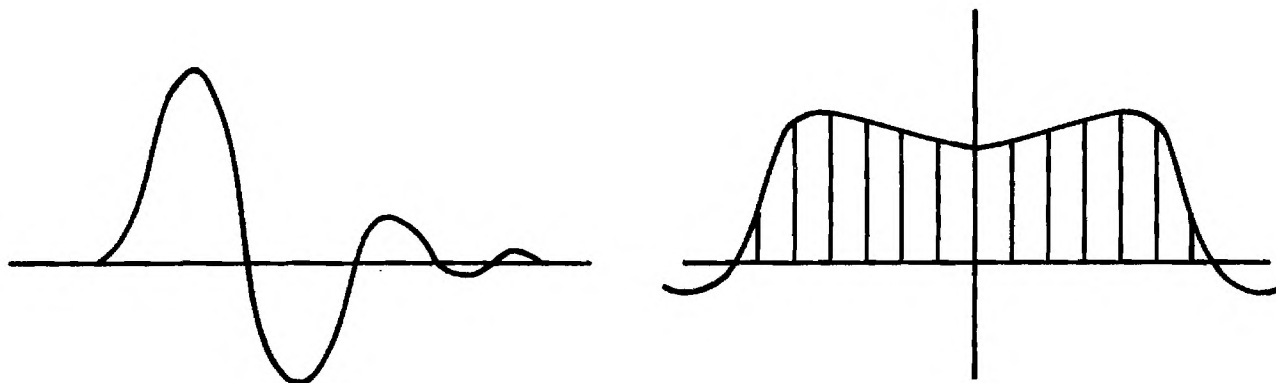


Figure 7.21. Waveform and Spectrum of Possible Synchronization Signal.

Synchronization of a free-running oscillator by a spectrum of the form just shown is theoretically possible at VHF and UHF, but the mechanics of producing the proper interrupted wave train are quite difficult. This topic for investigation was inactivated in order that more time might be devoted to other high-priority topics but the method of frequency control involved is believed to possess attractive potentialities.

E. Other Methods of Frequency Control at UHF

To the list of methods of or deviation for frequency control which have been already compiled, there may be added numerous devices which have been reported by other investigators. The literature cites many examples and authors such as Karplus, Isely, Slate, and Pound who have described the results of many experiments at high frequencies.

1. Wide-Range Tuned Circuits and Oscillators

One of the earlier reports by Karplus (12) on tuned circuits and oscillators at UHF described two fundamental types of tuned circuits which are applicable to the 500- to 1200-mc region. The first of these is the familiar butterfly circuit with certain innovations or modifications which appear to be advantageous. There will be cited, for example, a circuit designated as a semibutterfly. The circuit is illustrated in Figure 7.22.

The highest impedance in the circuit appears between the points 1 and 2 shown in the figure. In this unit, a solid rotor forms an eddy-current shield in the magnetic field and a series-gap capacitor with the stator plates. In this design, a wide tuning range is obtained by rotation of a member that does not require any electrical connections. The rotor shaft can be made of insulating material, and a flow of r-f currents through the bearings of this shaft is thus avoided. The rotor can be constructed as a solid block, a configuration which simplifies the mechanical details of assembly.

Although the author states that this circuit is easily applicable for frequencies as high as 1200 mc, no data are given as to oscillator performance. The circuit shown will probably suffer severe Q degradation at high frequencies caused by radiation, but complete shielding may partially obviate this difficulty. If the effective Q can be maintained at 300 or 400, then a reasonable order of frequency stability may be effected in an associated oscillator. Consideration is being given to the construction of a model for test purposes using Invar as basic material in order to reduce the temperature sensitivity of the unit.

Another basic type of circuit described by the same author is illustrated in Figure 7.23. It consists of two split cylinders mounted on a common axis and with an arrangement which permits a 180-degree rotation of the inner cylinder. Minimum effective frequency occurs when the two slots are adjacent since in this position the inductances of the two rings are essentially in parallel while the total capacity is not significantly different from that of a single slot alone. When the inside ring is rotated 180 degrees, as illustrated in Figure 7.23 C, the effective capacitance of the resonant circuit is greatly increased by the presence of the one ring across the gap of the other one while the effective inductance is also maximized.

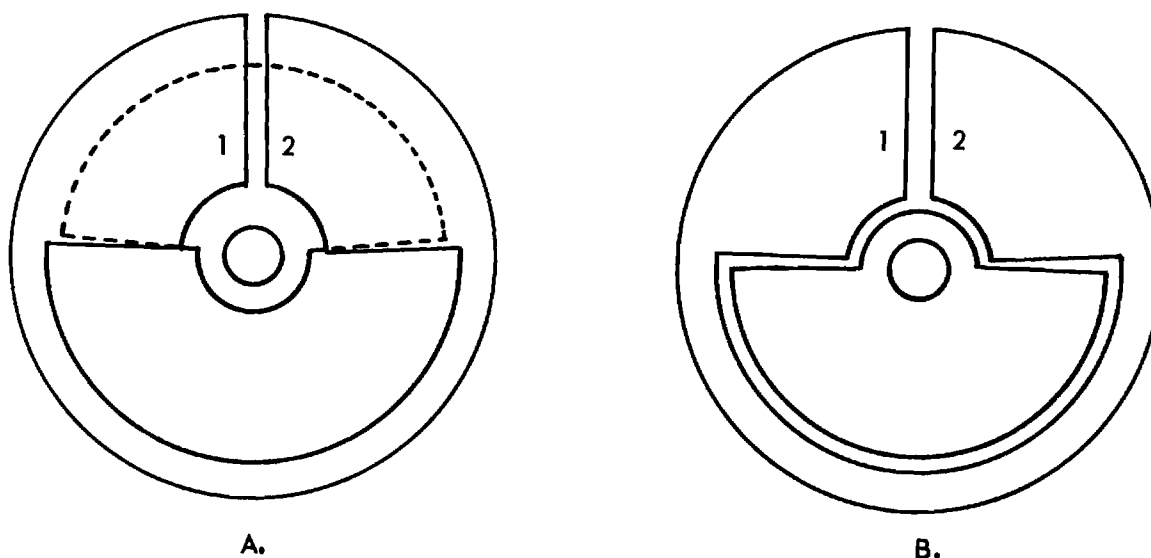


Figure 7.22. Stator and Rotor of Semibutterfly. (Frequency is minimum in A and maximum in B.)

At 1000 mc, a Q of not less than 1000 is claimed if the unit is suitably shielded. Local tests of test models have been conducted on this project to determine the characteristics of the circuit and associated oscillator. A configuration was used which consisted of an outer cylinder, two inches long with a 1-1/2-inch outer diameter and a 1/16-inch wall thickness. Inner cylinders were variously configured, some being equivalent in shape to the outer one, some being partially cut away to reduce the percentage change in capacitance and inductance per degree of rotation.

With these configurations, oscillations were easily obtained in the 500- to 1000-mc region utilizing the split-cylinder resonator as a two-terminal impedance shunted between plate and grid of a 6AF4 tube. A silver-plated shield enclosed the entire oscillator assembly to reduce Q -degradation caused by radiations. Although reasonable values of Q may be expected under these conditions, the frequency stability of the oscillator was not satisfactory, being no better than 6-ppm/v change of anode potential. In addition, the oscillator showed a marked

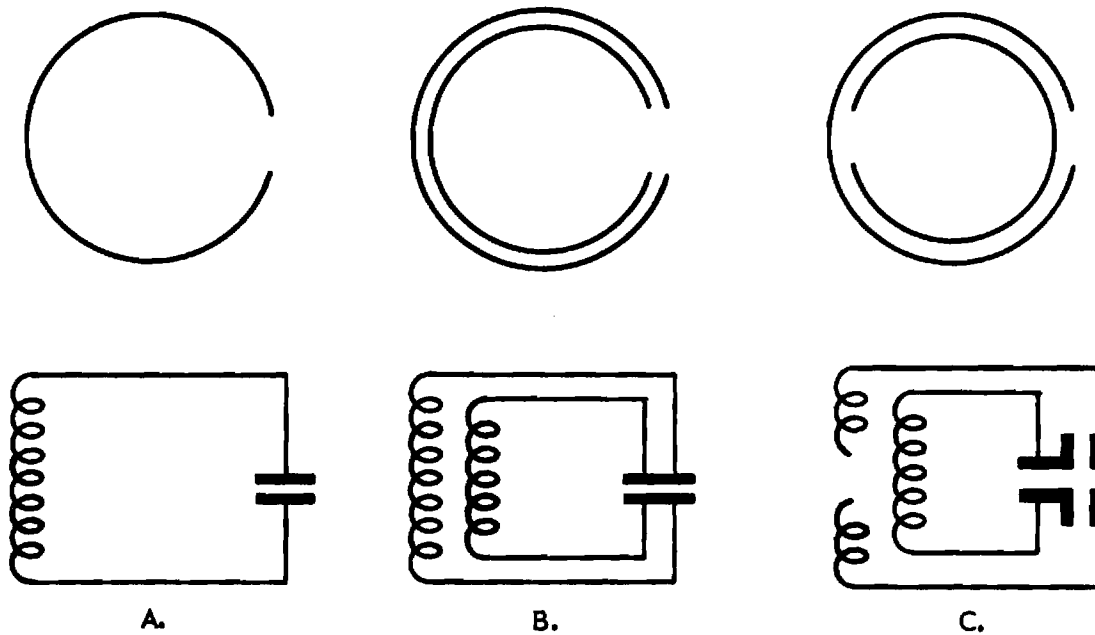


Figure 7.23. Representation of Split-Cylinder Resonator.

tendency to exhibit a discontinuous jump in frequency between the low and high ends of the band leaving a very large "hole" in the center portion. The results of this brief experiment have led to the conclusion that this configuration is basically unsatisfactory for stable frequency control, although it may find some use as a signal generator of limited tuning range and limited stability.

Isely (13) has described two types of circuits having distributed constants which are of considerable interest at UHF. The first of these utilizes a variable capacitor as a two-wire line as illustrated in Figure 7.24.

A commercial variable capacitor of the type normally used in broadcast receivers was recently tested at this project using the 6AF4 tube shunted across it, as illustrated in Figure 7.24. With rotation of the rotor plates, the discretely distributed capacity per unit length varies considerably. The oscillator, utilizing this capacitor, was found to have a tuning range of approximately

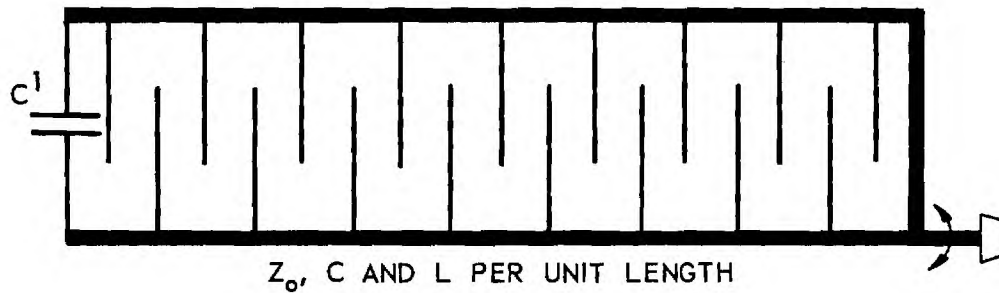


Figure 7.24. A Variable Capacitor as a Two-Wire Line.

520 to 620 mc. Complete shielding of the assembly was found to be necessary both to prevent excessive sensitivity to external factors and to prevent Q-degradation due to radiation. Stabilities slightly better than those found with the split-cylinder were measured. In addition, the oscillator was easy to tune and simple to construct. It suffers, however, from the fact that moving contacts are involved. It is concluded that this configuration, in its present form, is quite useful as a laboratory signal generator of moderate stability. It further appears that if moving contacts can be eliminated and if the capacitor is constructed of a material of low-temperature sensitivity that reasonable frequency control may be effected in a range not exceeding 1500 mc. Some tests in the 1000- to 1500-mc range may be conducted at a later date utilizing Invar as a basis for construction of the capacitor section.

The other type mentioned by Isely concerns a distributed-inductance line. This is constructed by using a solid outer conductor but utilizing a rotating off-center inner conductor. This inner conductor is solid in part but slotted in the remainder, so that during rotation an inductance variation is obtained by the variation of the mutual inductance when the solid portion approaches or recedes from an adjacent fixed member. A cross section of line is shown in Figure 7.25.

The configuration shown has moving contacts but these can be eliminated by utilizing a Bakelite (or equivalent) bearing, thus placing a capacitor across the otherwise shorted end of the line. This configuration shows some promise at

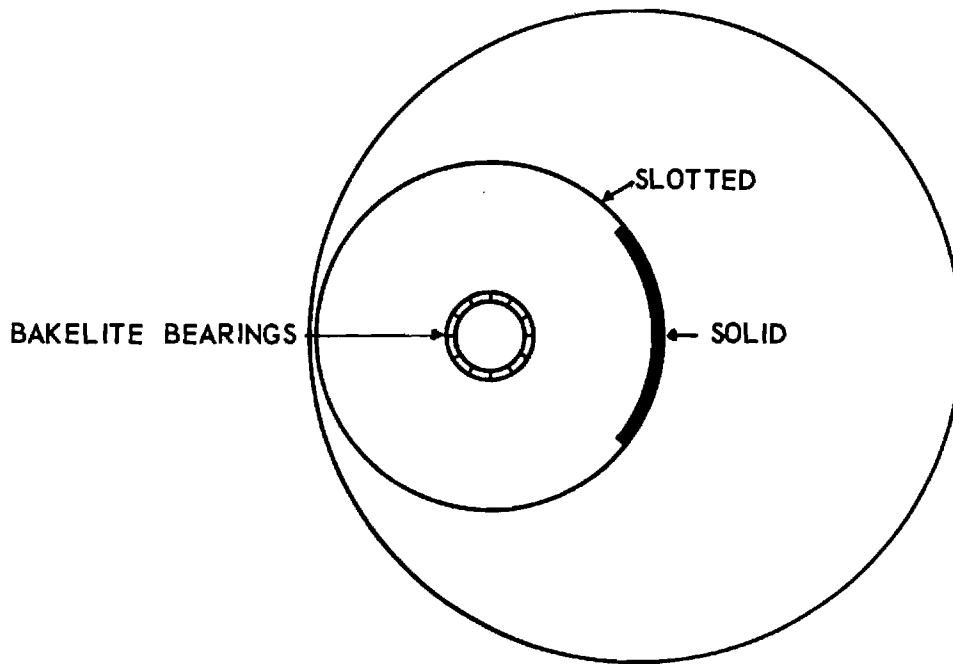


Figure 7.25. Cross Section of Distributed-Inductance Line.

frequencies up to 1500 mc. If time permits, a limited test of such a unit will be conducted.

Another paper (14) discusses a device which is not essentially different in principle from those previously mentioned but which is shown in Figure 7.26 to have considerable variation in mechanical detail. The resonant circuit, designated as a modified butterfly, uses a solid stator as a magnetic shield but provides a slot, or a cut-away section, for tuning purposes. Two separate versions of the circuit are shown in Figure 7.26. In the form shown at the left, the rotor is a solid semicylinder. The stator consists of a cylindrical metallic ring with a slot near the top plus two end plates. The rotor has a small clearance between the ends and the end plates attached to the stator.

In the form shown at the right, the end plates are omitted but the stator consists of a slotted semicylinder plus a narrow loop joining the two major portions. The rotor is also modified to become a solid cylinder with a single

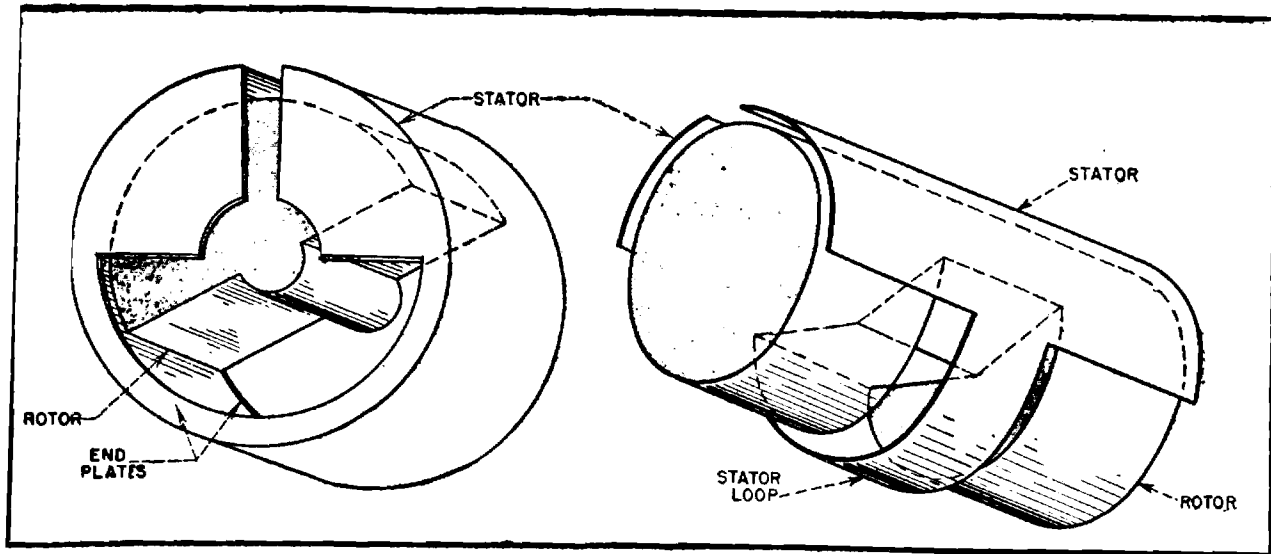


Figure 7.26. Two Versions of the Modified Butterfly.

transverse slot. The inductance variations now depend upon changes in inductance of the loop brought about by the shielding action of the rotor while the capacity variations are much the same as for the type with end plates.

The modified butterfly is claimed to provide linear tuning over an approximate two-to-one range between 500 and 900 mc. Consideration may be given to the possibility of extending its upper frequency range above 1000 mc and of utilizing low-expansion materials in construction.

Another method of control which has already been briefly mentioned is that of afc.

2. Automatic Frequency Control at UHF

The application of reflex-klystron oscillators as signal sources has focused attention on afc as a means of obtaining excellent frequency stability at UHF and SHF. The reflex klystron lends itself admirably to the afc process because a small change in reflector voltage produces a large change in oscillator frequency.

The basic method of providing the necessary circuit arrangements follows a system devised by R. V. Pound (15). Although his method is well-known, it is considered desirable to include a brief summary here to complete a partial resume of frequency-control methods.

The basic system, as described by Harrison (16), is shown in Figure 7.27. A hybrid junction furnishes a sample of the output of the klystron. When the oscillator frequency coincides with the resonant frequency of the cavity, there is no r-f signal at mixer crystal No. 1 and no i-f signal at mixer No. 2. A shift in frequency produces an r-f signal at the first crystal mixer which becomes modulated at the intermediate frequency and reflected to the second mixer where it is demodulated to produce an i-f signal. The phase and amplitude of the demodulated i-f signal are determined by the relation between the klystron frequency and the cavity frequency. The phase mixer compares the demodulated i-f with the original source and produces a signal which corrects the klystron frequency.

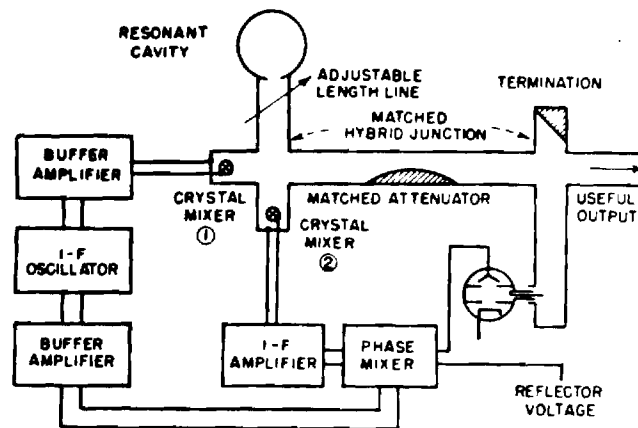


Figure 7.27. The Pound Stabilization System.

The possibilities of utilizing temperature-compensated coaxial cavities with this arrangement are self-evident and will be given careful consideration in the frequency regions above 1000 mc.

Stabilization systems such as that described by Pound are known to provide stable control of frequency above 2000 mc. At lower frequencies mechanical problems are posed by the increasingly large dimensions of waveguide and cavity. Below 1000 mc the system is not practicable in the configuration shown and some other form of frequency-sensitive device is needed if an equivalent afc system is to result.

One form of frequency-sensitive device which has demonstrated attractive characteristics at 500 mc is a cavity version of the high-frequency discriminator described in section B of this chapter. It may be theorized, and it has been demonstrated, that the resonator, (crystal of Figure 7.4) might be replaced by any equivalent high-Q resonator. The particular resonator selected was a coaxial cavity and the method of application is herewith described.

The arrangement which was used with a single cavity is illustrated in the sketch of Figure 7.28. The discriminator is shown schematically in the lower part of the figure, the curve of output d-c voltage is shown above. The cavity had a resonant frequency of about 496.1 mc. It will be noted that with an input of 1 volt rms a voltage swing of about 4/10-v, direct current results from a frequency variation of about 0.2 mc. This change is of sufficient magnitude to give promise of practical application, and might be improved upon by optimum selection of coupling loops within the cavity.

The selectivity of a discriminator using a cavity as the frequency-sensitive element theoretically can be doubled by making use of a second cavity which has a frequency which is adjusted so that the upper half-power frequency of one coincides with the lower half-power frequency of the other. In this case, if the discriminator is arranged to measure a d-c output, which is the difference of the rectified outputs of the cavities then the action will be as illustrated in Figure 7.29.

The description of the forms of discriminators shown in Figures 7.28 and 7.29 concludes this brief summary of varied methods of control of high frequencies. Some of the methods shown are simple in form but do not provide stable outputs, others are less simple but exhibit more stable characteristics. The choice of device will be dictated by the particular requirements of any particular activity.

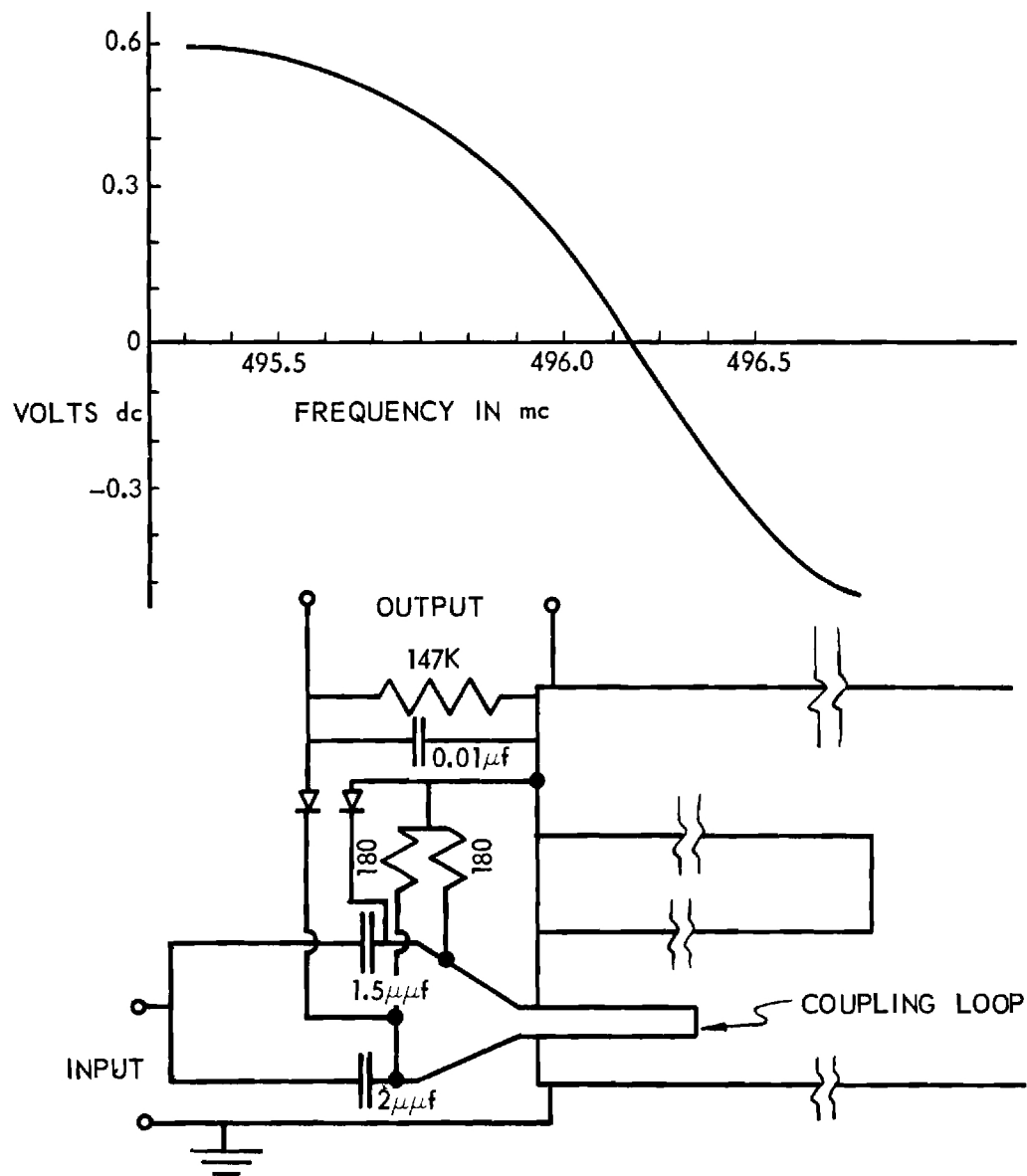


Figure 7.28. Discriminator and Output Utilizing Coaxial Cavity.

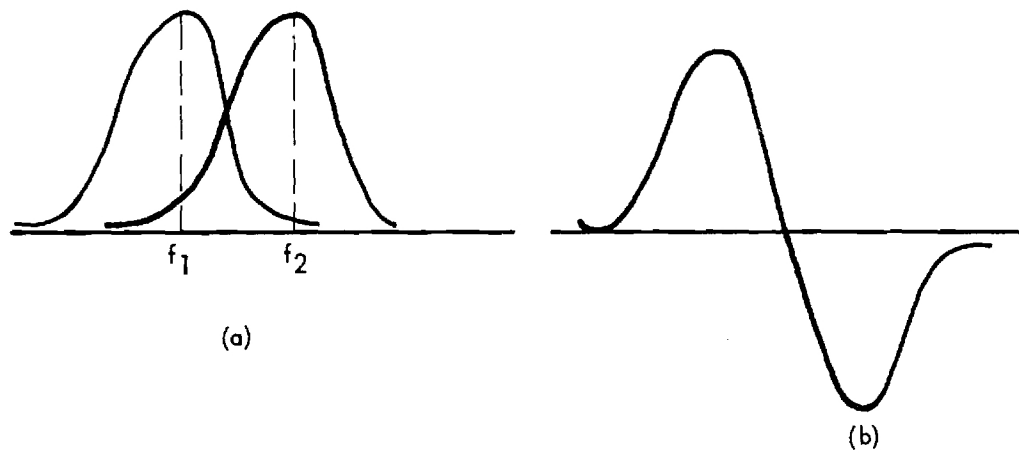


Figure 7.29. Double-Cavity Discriminator Action.

VIII. MEASUREMENTS OF FREQUENCY AND OF Q AT UHF

A. Introduction

The design and construction of precision frequency control devices requires the availability of testing equipment with which to determine the stability of final assemblies. In the early days of the present contract, no equipment was available by which either frequency or frequency drift could be determined accurately in the UHF region. However, the situation was considerably improved by the acquisition of a Gertsch FM-3 frequency meter. This meter has an accuracy of one part in 10^5 and has a short-term stability, defined in terms of drift around the center frequency, which has been demonstrated to be at least one order of magnitude better. Hence, this meter has been invaluable in determining such items as effect of plate and filament voltages on the frequency of an oscillator under test and in measuring the frequency drift of resonant cavities under the influence of varying ambient temperatures.

The completion of oscillators with nominal frequencies of 600 mc, 800 mc, and 1000 mc resulted in a need for frequency-measuring equipment having relatively high orders of accuracy. In order to satisfy this need, a frequency-measuring system was assembled which permits both short-term and long-term frequency measurements not only in the specified range but also at other frequencies from the audio range upward. The first version of the system performed satisfactorily at the frequencies of 620 and 800 mc. No measurements have as yet been made above 1000 mc, but the system is designed to accommodate frequencies as high as 3000 mc. The next section of this report describes the system in some detail and comments upon its accuracy and the magnitude of signal required for proper operation.

B. Outline of the System

The system is comprised basically of a heterodyne assembly, beat-frequency amplifiers, and a frequency counter. The stabilities required are established by the introduction of stable signals from each of two secondary frequency standards. One of these is a 100-kc Loran standard, and the other is a 50-mc crystal-controlled oscillator with special design features to improve stability.

The operation of the system is best illustrated by reference to the block diagram of Figure 8.1. The applicable frequencies as well as their orders of stabilities are indicated thereon. Harmonics of 50.0 mc mix with the output of the oscillator under test. The amplified difference frequency is fed to the frequency counter where further heterodyne action occurs reducing the signal to a frequency of less than 1 mc. It is then counted, and its value indicated on a decade display system.

1. Description of Units

a. The 50-Mc Secondary Standard. This unit is based upon a crystal-controlled oscillator which employs the third overtone of a $16\frac{2}{3}$ -mc crystal in a C. I. Meter circuit. A buffer and an output amplifier complete the signal channel. A regulated power supply is contained in the same chassis and also a thermostatically controlled oven whose purpose is to maintain constant temperature on the crystal. A Lavoie type K0000-0006 oven is utilized in this assembly.

Relative insensitivity to variations in ambient temperature is achieved by the crystal oven and by utilization of variable capacitors with low temperature sensitivity. These capacitors, which individually tune the plate and the grid quarter-wave lines, are type VC-11, manufactured by the JFD Company. They have a claimed temperature coefficient of zero.

The circuit of the signal channel is shown in Figure 8.2. The output into a 100-ohm cable is nominally 3-volts rms.

b. Harmonic Multiplier. The harmonic multiplier is a commercial unit available under the trade name of the Presto Microwave Secondary Frequency Standard, Model 100. In its original form, it includes a self-contained, 50-mc, crystal-controlled oscillator. This crystal is not enclosed in an oven, hence suffers from temperature effects. For this and other reasons, the internal oscillator was inactivated and utilized as an amplifier for the 50-mc signal originating in the 50-mc secondary standard.

A block diagram of the equipment is shown in Figure 8.3. The 200-mc signal, containing also 50- and 100-mc components of considerable magnitude, is injected into a silicon-diode crystal. The combined holder and diode is of a

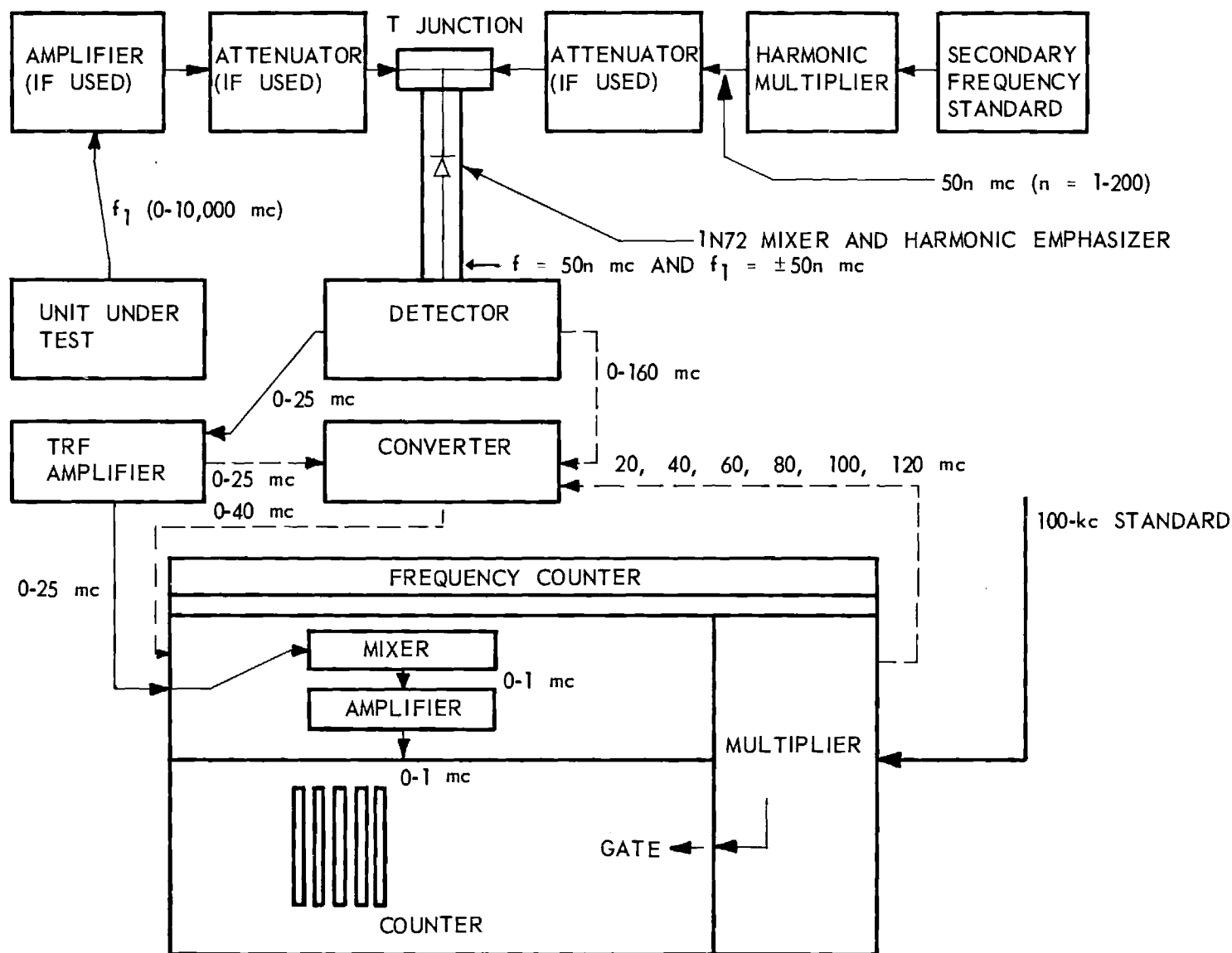


Figure 8.1. Block Diagram of Frequency-Measuring System.

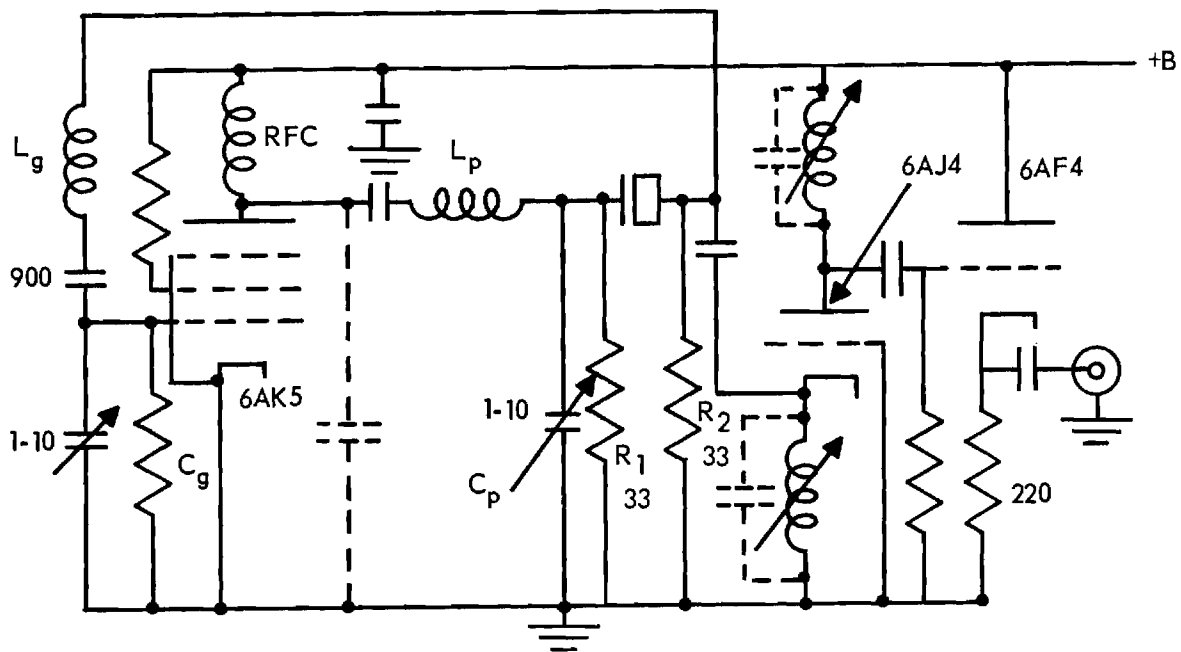


Figure 8.2. A 50-Mc Oscillator as Secondary Standard.

special design stated to incorporate features which enhance microwaves. The output consists of a harmonic series of uninterrupted c-w markers. The power level at any particular frequency is stated to be inversely proportional to its harmonic number. However, in the range of 600 to 1000 mc considerable variation in the individual strengths of the various 50-mc harmonics has been found, the multiples of 200 mc being considerably stronger than those of 100 mc and 50 mc.

c. Mixers and Detectors. Inasmuch as the mixers and detectors may be expected to be fed from low-impedance sources, at UHF and microwaves, it may be anticipated that crystals having relatively high conductivity would give a more satisfactory output than would crystals of higher impedance. This has been found to be the case in the 500- to 1000-mc range. A type 1N72 germanium diode has proved to be the most satisfactory of any utilized.

d. The 100-Kc Secondary Standard. This signal originates in a Western Electric type D-175730 Frequency Standard, is amplified, multiplied to 1 mc and fed by a cathode follower into a coaxial cable. The standard itself remains immobile, but the amplified and multiplied signal is delivered by cable to several research areas in order to permit mobility of the complete frequency-measuring system.

This 100-kc standard is checked daily during working hours against WWV. It has consistently demonstrated an accuracy of considerably better than one part in 10^8 , hence the stability of the gate in the counter is of the same order of accuracy.

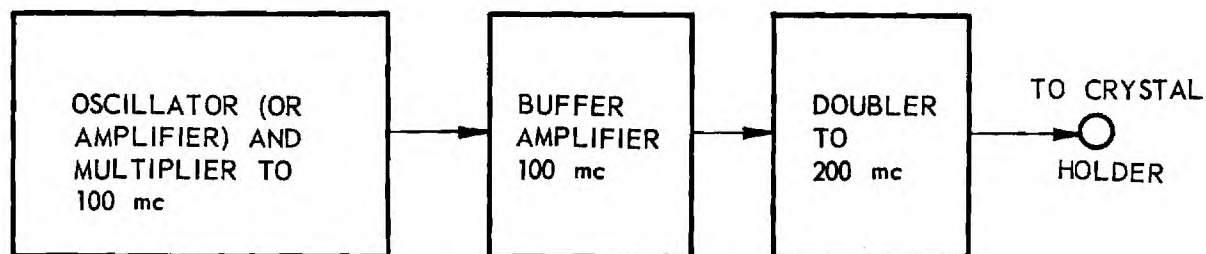


Figure 8.3. Block Diagram of Harmonic Generator.

e. The Frequency Counter (and Converter). The counter system, as presently employed, consists of two basic units. One is a Berkeley type 5575 VHF Frequency Converter, and the other is a Berkeley Type 5570 Frequency Meter. The converter is available for the purpose of reducing frequencies by heterodyne action to frequencies of less than 40 mc. The converter will accept signals of not greater than 160 mc and the frequency counter will measure frequencies of less than 41 mc.

The required accuracy is again based upon the 100-kc standard. This stable signal is multiplied to 1 mc and injected into the frequency counter where it replaces an internally generated signal of the same nominal frequency. Further multipliers and harmonic emphasizeers produce integral multiples of 1 mc, each multiple having the same nominal accuracy as the original 100-kc signal. The frequency to be measured is heterodyned against one of these harmonics and reduced to a frequency of less than 1 mc. It is then applied to the counter system proper where it is counted during a two-second interval. The accuracy of the counting period, or gate, is controlled by the 100-kc standard by means of a dividing network.

The maximum error in determining any frequency is the sum of the maximum errors of the 50-mc secondary standard, of the 100-kc standard, and of the counter system. The stability of the 50-mc standard is about one part in 10^7 ,

measured over a period of one day, and is considerably better for shorter periods of time. The 100-kc standard has a stability of not worse than one part in 10^8 . The counter system, using the accurately controlled gate, demonstrates no relative error except for an inherent plus-or-minus one count in a counting interval.

From the foregoing discussion, it is seen that the accuracy of measuring frequencies above 160 mc is determined for the most part by the 50-mc secondary standard if readings are taken over an interval of several hours. This implies, of course, that the 50-mc standard is checked only at the beginning of the measurements. If a frequency of 620 mc is to be measured, for example, the 12th harmonic of the 50-mc oscillator is utilized in the heterodyne action. This 12th harmonic has an error of no more than 60 cycles, and hence the difference frequency is then 20×10^6 cycles plus or minus 60 cycles. The nominal 20-mc difference frequency has thus been measured within 1 part in 10^8 plus or minus 1 cycle, or a total possible error of 1.2 cycles. The 620-mc measurement is less than 62 cycles in error which is 1 part in 10^7 , as measured over a period of several hours.

An accuracy of one part in 10^7 is considered to be satisfactory for measurements being made at present. If higher orders of accuracy are needed, it will be necessary to monitor the 50-mc standard. If this is done, then an accuracy of one part in 10^8 could be anticipated.

C. Cavity Q-Meter Technique

1. Requirements of a Cavity Q-Meter

The frequency-measuring equipment just described facilitates the determination of the frequency of active oscillators but is not designed to measure the resonant frequency of passive networks. Inasmuch as considerable effort has been directed, on this project, to a determination of the frequency-temperature characteristics of cavity resonators, it was evident that equipment additional to that just described would be required.

A well-known technique for determining the response of a tuned circuit is the so-called "swept-frequency" process. In this technique, an f-m signal is impressed upon the tuned circuit and the magnitude of signal transmitted by the

circuit is observed or recorded by appropriate equipment. If all portions of the equipment exterior to the circuit under test are non-frequency selective, it is possible to obtain a measured output which is a true frequency response curve of the tuned circuit. The essential requirements of such a system include the following: (1) it must be capable of producing an f-m signal which shall have negligible amplitude modulation and which is capable of sweeping a frequency band considerably greater than that represented by the frequency response band of any circuit under test, (2) it must be conveniently tunable and should desirably exhibit a relatively high order of frequency stability, and (3) it must include an output circuit which exhibits an amplitude response which is linear with respect to amplitude of the signal transmitted through the cavity. The last requirement may be modified to permit some non-linearity by preparation and use of calibration curves of output-versus-input amplitudes.

Although the basic equipment discussed is capable of producing an output which is proportional to the response curve of the tuned circuit, it is incapable of providing further data without additional components. If, as usual, the observing and/or recording device is a cathode ray oscilloscope, a visual picture of the response curve is presented but such factors as center frequency, f_a , and bandwidth, $f_2 - f_1$, cannot be determined. It is the purpose of this section to describe an apparatus which permits rapid determination of f_a , the center frequency, of $f_2 - f_1$ the bandwidth (and hence Q by the relationship $Q = f_a / (f_2 - f_1)$) and of variations in these due to various controlled parameters. Inasmuch as the tuned circuits concerned in the project consist of coaxial cavities, the name cavity Q-meter is appropriate.

2. Components of the Cavity Q-Meter

The basic plan as outlined by Young (17) was adopted for the initial layout of a Q-meter. Numerous changes were later incorporated to permit a maximum of utilization and of flexibility.

The components for the Q-meter are shown in Figure 8.4. R-F power in the UHF region is generated by an f-m oscillator and is transmitted through the test cavity to a detector. The detected, amplified signal drives the vertical deflection plates of a cathode ray oscilloscope. The output of the f-m oscillator is also fed to a mixer where heterodyne action occurs with a signal from

the variable frequency oscillator. The difference frequencies in the mixer output are now subjected to selective, narrow-band filtering in the band-pass amplifier. By a proper setting of each oscillator, it is possible to

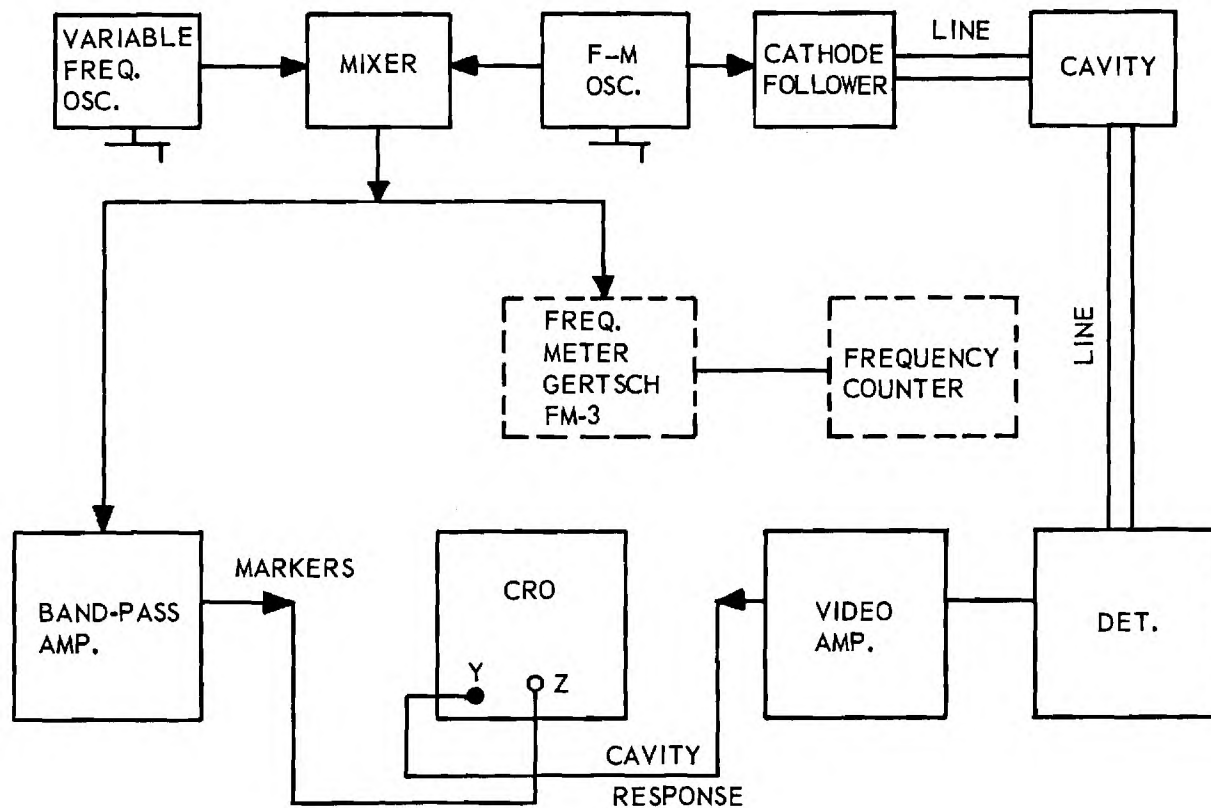


Figure 8.4. Block Diagram of Cavity Q-Meter.

produce difference frequencies at two different points when the f-m oscillator is either above or below the frequency of the variable oscillator. These difference frequencies will be transmitted through the band-pass amplifier. The presence of high-Q tuned circuits in this amplifier assures that the tube transmissions consist of pulses which have large amplitude but are relatively narrow. These pulses, when amplified, are used to intensity-modulate the cathode-ray tube and thus produce spots, or markers, on the response curve of the cavity. When these markers are adjusted so as to be equidistant from the baseline, the variable oscillator will be generating a frequency which corresponds to the resonant frequency of the cavity. If the band-pass amplifier is adjusted so that the spots occur at the cavity half-power points, their frequency separation is equal to the bandwidth of the cavity.

Frequency measurements may be made in several ways, but a method that has been found to be satisfactory at frequencies up to 1000 mc is described as follows. A UHF signal generator of moderate-to-good stability is loosely coupled into the r-f system of the Q-meter. The frequency of the output of this signal generator is adjusted until approximately coincident with the nominal resonant frequency of the cavity. This approximate coincidence is visually indicated by the appearance of a "pip" or marker on the response curve already generated on the CRO of the cavity Q-meter. The marker is alternately adjusted in position and attenuated in amplitude until it appears as a fine line superimposed upon the tip of the response curve. The definition of line and curve and determination of the extreme tip of the curve have been considered to be satisfactory. A resettability of no worse than 4 kc has been demonstrated at a nominal center frequency of 800 mc. If the cavity resonator is heatcycled and is subjected to a change in temperature of about 70° C (representative of many of the tests conducted), a possible maximum error of 4 kc represents less than 1/10 ppm/°C.

The actual measurement of frequency is made by the system described in the previous section. The output of the signal generator, the "pip" generator, is monitored continuously and its frequency is recorded at appropriate intervals.

A schematic of an early version of the cavity Q-meter is shown in Figure 8.5. This equipment operated satisfactorily at frequencies up to 600 mc, but difficulties were experienced with the f-m oscillator at higher frequencies. At a later date, commercial signal and swept-frequency generators became available and were employed in place of the locally constructed f-m and marker oscillators.

3. Requirements for Obtaining Significant Measurements

The measurement technique outlined in the introduction to this section is valid provided the linearity and non-frequency selectivity of circuit parameters is maintained. The most serious difficulty encountered is that of eliminating the impedance variations which occur in the transmission lines used for coupling purposes. It is often desirable to separate the cavity and Q-meter, an example of this condition occurs when the cavity is inserted in a heat chamber where its frequency-versus-temperature response can be conveniently

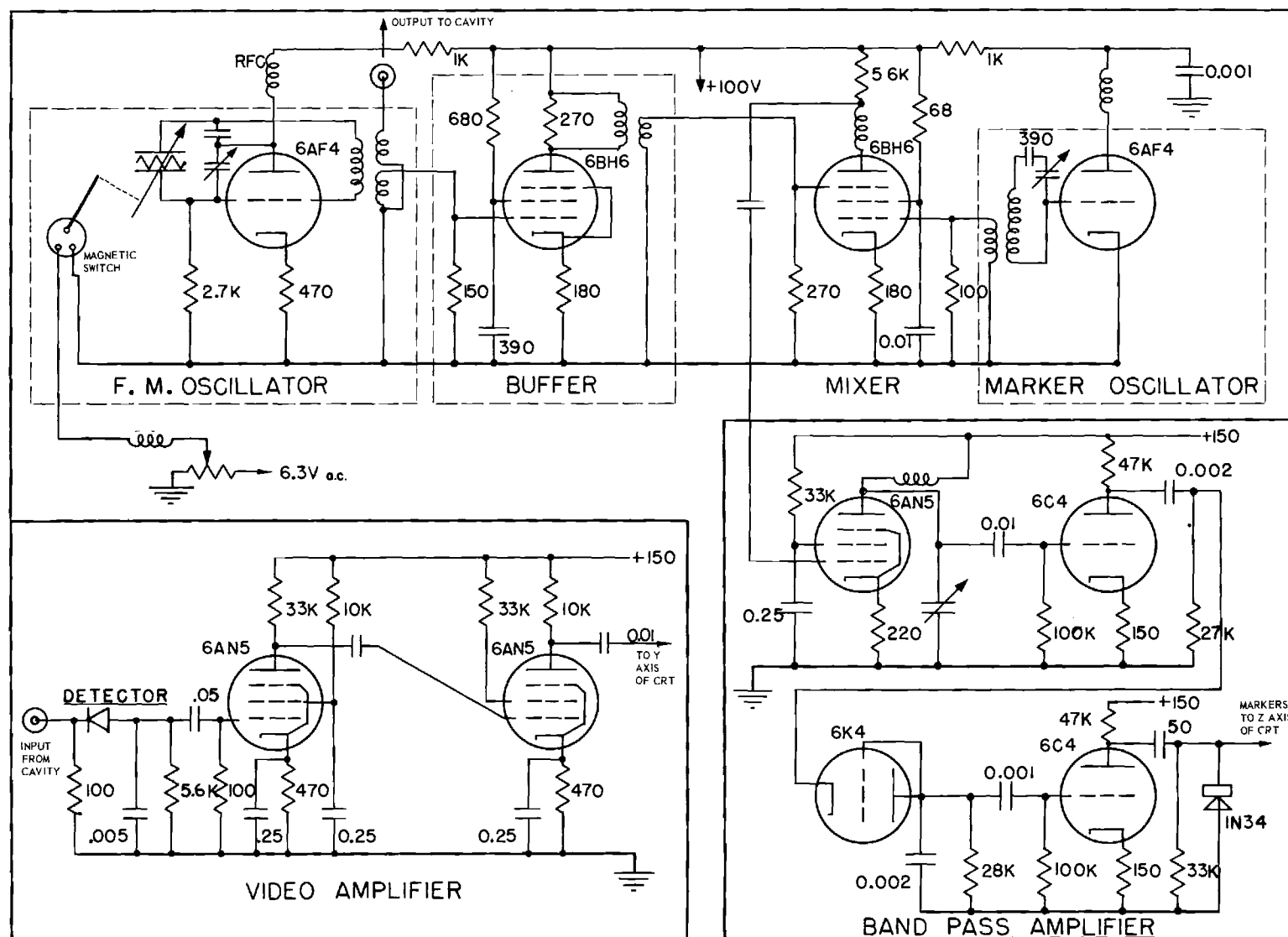


Figure 8.5. Schematic Diagram, Cavity Q-Meter.

attained. In this case, several feet of coaxial cable are required to couple the cavity to the Q-meter. Unless the lines and their terminations are quite carefully matched, the variable impedances reflected both into the oscillator and into the cavity may result in such adverse effects as frequency pulling of the oscillator and apparent distortion of the cavity response.

One method of sharply reducing these impedance variations is to place resistive attenuators in the line. The apparent mismatch due to an improper line termination may be considerably reduced. A 6-db resistive pad, for instance, will reduce a 3:1 VSWR to the relatively satisfactory value of 1.3:1. If sufficient driving voltage is available, then it is advantageous to employ 10-db or possibly 20-db resistive attenuation between signal generator (f-m oscillator) and cavity. Attenuation on the output side may be employed but is much less important there because the output feeds into a detector circuit which presents a nearly constant impedance to the cavity during the "swept-frequency" period.

It is evident that the response curve of the cavity represents that of a loaded circuit, since the input and output circuits are attached to relatively low impedances which will be reflected, in whole or in part, into the cavity and will act either to change its resonant frequency or degrade its Q. It is quite necessary to evaluate the cavity and coupling parameters in order that the response curve of the cavity may be properly interpreted. The succeeding paragraphs summarize several formulas which permit calculation of the desired size of coupling loop and of the effect of the loads upon the cavity.

4. Q-Factors, Coupling Parameters, and External Loading

It is convenient to begin an analysis of the quantities involved in measurement by reviewing the methods of representing the parameters of a cavity and of determining proper coupling values. These items were discussed in detail in the previous project (18) and are briefly summarized here for convenient reference.

A quarter-wave coaxial resonator may be represented by the equivalent lumped parameters of Figure 8.6.

The characteristic impedance Z_o of a coaxial line is given by:

$$Z_o = \frac{1}{2\pi} \sqrt{\frac{\mu_1}{\epsilon_1}} \ln(b/a) \text{ ohms} \quad (8.1)$$

where μ_1 and ϵ_1 , are the permeability and permittivity of the medium between the inner and outer conductors.

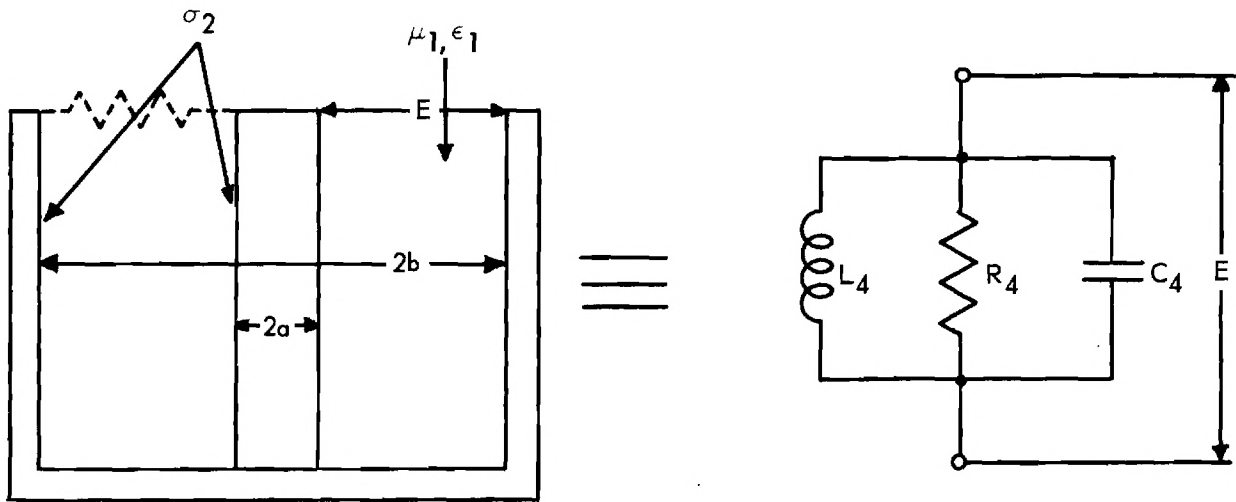


Figure 8.6. Quarter-Wave Coaxial Resonator.

In terms of the equivalent circuit, Z_o is given by:

$$Z_o = \pi/4 \sqrt{\frac{L_4}{C_4}} \text{ ohms.} \quad (8.2)$$

The parameters of the equivalent circuit of the quarter-wave resonator in terms of line constants are given in the following expressions:

$$C_4 = \pi/4 Z_o \omega_a = x_o/2Z_o \text{ farads} \quad (8.3)$$

$$L_4 = 4Z_o/\pi\omega_a = 8x_o Z_o/\pi^2 \text{ henries} \quad (8.4)$$

$$R_4 = Z_o/\alpha x_o \text{ ohms} \quad (8.5)$$

Equations 8.3, 8.4, and 8.5 give the element values of the equivalent circuit which approximates the open-end impedance of the resonator. This approximation is excellent in the region of antiresonance but fails at higher and lower frequencies.

The parameters listed in these formulas are defined as follows:

$$\omega_a = \pi v / 2x_o = 2\pi f_a = 1/\sqrt{L_4 C_4} \text{ radians/second} \quad (8.6)$$

$$v = 1/\sqrt{\mu_1 \epsilon_1} \text{ meters/second} \quad (8.7)$$

$$x_o = \lambda_a / 4 \text{ meters} \quad (8.8)$$

and

$$\alpha = 1/2 \sqrt{\frac{\pi^2 \mu_2 \epsilon_1}{\sigma_2 \mu_1}} (1/b + 1/a) \frac{1}{\ln(b/a)} \text{ nepers meter} \quad (8.9)$$

The Q, or selectivity of the resonator is given by:

$$Q = R_4 / \omega_a L_4 = R_4 \omega_a C_4 = \pi f_a / \alpha v. \quad (8.10)$$

Although various means of coupling can be utilized, the present method employed is as shown in Figure 8.7. The equivalent parameters of the cavity, when transformed by the impedance ratio of cavity to loop, are represented in the right section of the figure.

The impedance at the loop terminals may be determined by assuming a peak current, I_m , to be flowing at the short circuit end of the cavity. From the known sinusoidal distribution of the magnetic field due to this current, the voltage induced in the loop and at the open end of the cavity may be determined. If this is carried through, there is obtained for these voltages the expressions:

$$E_{\max} = \frac{\omega \mu_1 I_m x_o}{2\pi} \sin\left(\frac{\pi}{2}\right) \ln(b/a) \quad (8.11)$$

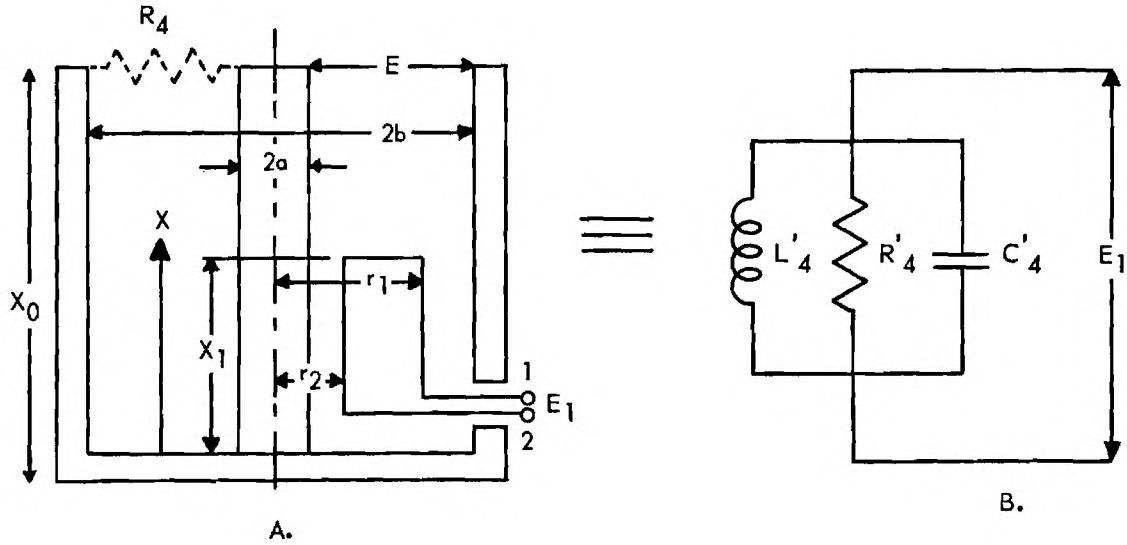


Figure 8.7. Coupling Methods.

$$E_1 \max = \frac{\omega \mu_1 I_m x_0}{\pi^2} \sin \left(\frac{\pi x_1}{2 x_0} \right) \ln \frac{r_2}{r_1}. \quad (8.12)$$

Equating E^2/R_4 to E_1^2/R_4' , one obtains:

$$R_4' = R_4 \left[\frac{\ln(b/a)}{\sin \left(\frac{\pi x_1}{2 x_0} \right) \ln \frac{r_2}{r_1}} \right]^{-2} \quad (8.13)$$

This relationship given in equation 8.13 is convenient in calculating either the equivalent impedance of a coupling loop of known size or conversely of determining the required length of the coupling necessary to provide a desired impedance. A simple example will indicate the order of magnitude of several of the above quantities. The cavity under consideration consisted of silver-plated conductors with $2b = 6.3$ cm, $2a = 1.3$ cm, and $x_0 = 25$ cm. For this resonator, $R_4 = 1,200,000$ ohms, $L_4 = 0.067$ μ h, $C_4 = 4.3$ μ mf, $Z_0 = 100$ ohms, $\alpha = 3.4 \times 10^{-4}$ nepers/meter, and $Q = 9300$. This cavity was coupled to the cavity Q-meter by coaxial cables of $Z_0 = 180$ ohms. Utilizing equation 8.13, it was found that a loop length of approximately 0.8 cm will provide an impedance,

at f_2 , of about 180 ohms. The input and output coupling loops were thus made 0.8 cm long to assure the semi-matching discussed earlier in this section.

5. Loaded and Unloaded Q's

The cavity, complete with input and output coupling loops may be conveniently represented by Figure 8.8 A. The coupling loops are replaced by ideal transformers having impedance transformations of N_1^2 and N_2^2 respectively. If the leakage inductance of the loops is neglected as being negligible, than an equivalent lumped equivalent of the cavity, valid at f_a , is shown in Figure 8.8 B.

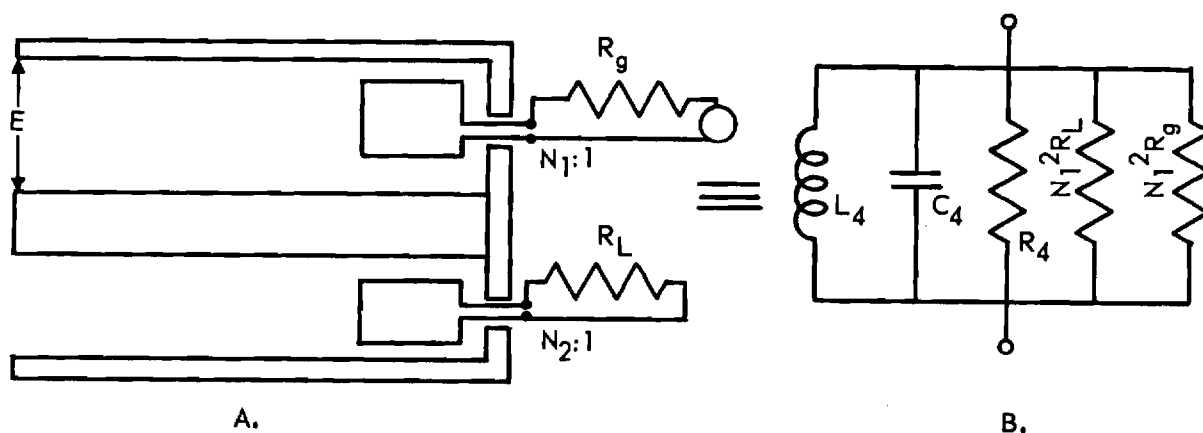


Figure 8.8. Equivalent Circuit of Cavity and Coupling Loops.

The loaded and unloaded Q's of the cavity can be now defined in terms of the parameters of Figures 8.6 and 8.8.

$$Q_u = \text{unloaded } Q = \frac{R_4}{\omega_a L_4} \quad (8.14)$$

One can likewise define a loaded Q by:

$$Q_L = \text{loaded } Q = \frac{R_4}{\omega_a L_4} \quad (8.15)$$

where R_o , from Figure 8.8 B is given by:

$$R_o = \frac{1}{\frac{1}{R_4} + \frac{1}{N_1^2 R_g} + \frac{1}{N_2^2 R_L}} \quad (8.16)$$

from which it is evident that

$$Q_u = Q_L (R_4/R_o). \quad (8.17)$$

If R_g and R_L are chosen to equal the Z_o of the coupling lines, and further if N_1 and N_2 are each chosen so that

$$\frac{1}{N_1^2} R_4 = Z_o = \frac{1}{N_2^2} R_4$$

then

$$R_o = 1/3 R_4 \text{ and } Q_u = 3Q_L.$$

This is the condition which is established if the matched conditions are obtained.

The obvious disadvantages of the method of matching utilized here is that the impedance of the input coupling loop varies rapidly near f_a and that this variation is reflected to the cathode follower output and in reduced magnitude to the oscillator output. However, two distinct advantages appear to be gained by not using attenuators with a possible total loss of 25 to 30 db. The first is that the size of the coupling loops into the cavity may be greatly reduced (for example, when attenuators totaling 30 db were used the input loop was required to be 3 cms long whereas a length of only 0.8 cm was used in the absence of attenuators). The second is that the oscillator may be much more lightly coupled to the line than was possible when high losses were present.

IX. CONCLUSIONS AND RECOMMENDATIONS

A. Summary of Results Achieved

1. Design of fixed-frequency cavities in the UHF region which by means of temperature-compensation principles achieve very low temperature sensitivity.
2. Design of temperature-compensated tunable cavities which also demonstrate small temperature sensitivity in the UHF region.
3. Design of oscillators employing type 6AF4 vacuum tubes internal to Invar coaxial cavities and utilizing direct cavity control to achieve high orders of stability.
4. Design of oscillators employing pencil-type triodes internal to coaxial cavities and utilizing re-entrant principles to achieve high orders of stability.
5. Establishment of preferred methods of fabricating, silver plating, and soldering the component materials of resonant cavities.
6. Development of methods of accurate measurement of frequency and cavity characteristics at UHF.
7. Compilation of a summary of diverse methods of frequency control at UHF.

B. Frequency Control Problem at UHF

If a cavity is used to control the frequency of a UHF source, the engineer is confronted with a problem of materials to be used. A metallic base cavity that can be easily plated with gold or silver is a desirable type but, at the present state of the art, there is no known metal which does not exhibit a finite expansivity. The expansivity of Invar, the nickel-steel alloy, has been reduced to less than one ppm/ $^{\circ}$ C, but recent investigators have found that the slightest trace of impurities in the alloy seriously impairs its temperature insensitivity. Invar has, however, a desirable property of slow conduction of heat whereby rapid fluctuations of ambient temperature are essentially isolated from vacuum tubes and other components which are mounted interior to an Invar cavity.

Other materials which have been employed as bases for cavities include fused quartz and a porous ceramic with the trade name of Stupalith. The latter material is potentially a very desirable type to be used in the fabrication of cavity resonators since it may have either a zero or a negative coefficient of expansion. However, considerable care must be exercised in silver plating and in soldering to this material because the porous base has relatively small mechanical strength and tends, in addition, to entrap moisture or gases which may adversely affect the silvered surfaces. Careful methods of preparation, plating, and soldering described in this report now appear to have alleviated many of the difficulties arising during utilization of Stupalith.

Cavities constructed of materials with small expansivity have not, in general, demonstrated those frequency-temperature characteristics which might be predicted from the known properties of the base material. However, other cavities have been designed and constructed which attain virtually complete temperature insensitivity by means of a compensation principle. Compensated coaxial cavities utilize a principle by which the unequal expansivities of two materials are employed to neutralize the normal effects of thermal expansion upon the inner conductor. Those cavities constructed in the course of the present investigation employed outer conductors made of brass and inner conductors formed from silver-plated Pyrex, Vycor, or Invar. The inner conductor extended into an extra (compensating) section of brass whose length was the product of the inverse ratio of the expansivities of the material and the length of the inner conductor. These cavities exhibited, in general, frequency changes of about 0.5 ppm/° C and in some cases exhibited essentially zero changes.

Compensated cavities have not been employed in active circuits, although methods by which to utilize cavities as components of high-frequency oscillators are known. There are, in fact, three quite distinct methods by which high-Q resonators are employed to produce stable high-frequency oscillations. Possibly the most common method is that of indirect control through AFC circuitry with the cavity forming one arm of a r-f bridge. The well known Pound system (15) is an example of such utilization. Another method is one in which the initial oscillation is stabilized by piezoelectric quartz crystals at a relatively low frequency and

is multiplied to the desired final high frequency in a series of steps. Both systems can be made to produce stable oscillations at high frequencies but a large number of components are required. Multiplication systems, in addition, are prone to suffer from the introduction of considerable phase modulation during the multiplication process.

The disadvantages of the previously listed systems may be improved upon or completely eliminated by a method of direct cavity control of an oscillator at the final desired high-frequency. If the oscillator tube is interior to the cavity, if the effective Q of the loaded cavity is high, and if the assembly is quite insensitive to fluctuations in ambient temperature, then the assembly may be superior to other types in many applications. Investigations of two types of cavity-controlled oscillators have been conducted in the 500- to 1000-mc region, and encouraging results have been obtained. Each of these types is described in the following paragraphs.

C. Preferred Oscillator Assemblies

A UHF oscillator, with nominal center frequency of 600 mc and with tuning range of ± 5 per cent, was constructed in a form which employed a high-frequency triode (type 6AF4) enclosed within the center conductor of coaxial cavity. Temperature sensitivity was minimized by the use of Invar for all elements of the cavity and oscillator instabilities were reduced by a series-capacitor coupling between cavity and tube. The frequency stability of this oscillator, under conditions of stabilized voltage and temperature, was tested under carefully controlled conditions by comparison (by a beat-frequency technique) of the Invar-formed cavity-controlled oscillator and a brass prototype. Automatic recordings of the beat-frequency variation demonstrated a change of less than 30 cycles in 1/2 hour and of less than 250 cycles in 15 hours. The first of these variations, at the frequency involved, is less than 5 parts in 10^8 .

Later tests employed direct frequency measurements with an equipment capable of high accuracy (one part in 10^8), and studies were made of the effects of fluctuations of ambient temperature, of frequency drift during warm-up, and of frequency shift due to changes in filament voltage. The results obtained led to the following important conclusions: (a) The oscillator is almost completely

insensitive to rapid fluctuations (in the order of minutes) of ambient temperature about a mean. This insensitivity is due to the extremely slow conduction of heat throughout the Invar cavity. (b) The primary source of frequency drift during warm-up is due to the tube rather than the cavity. The frequency change during warm-up of a nominal 600-mc oscillator was measured as 44 kc during the first hour, 30 kc of which occurred during the first five minutes. (c) The oscillator is relatively insensitive to changes of filament voltage because of the slow conduction of heat from the tube to the cavity.

A second type of cavity utilizes a type 5876 pencil triode and achieves feedback by direct coupling between a plate-to-grid cavity and a grid-to-cathode cavity. This device is termed a re-entrant type oscillator because the feedback region is essentially interior to the frequency-controlling cavity. Oscillators of this type have been successfully operated at nominal frequencies of 600, 800, and 1000 mc and have indicated potential stability characteristics similar to those of the oscillator described in the previous paragraph.

D. Remaining Problems

The state of the art regarding precision frequency control at UHF is not clearly defined at the present time. Some very precise and accurate oscillatory systems have been devised, such as the cesium line oscillator, but these are thus far restricted to narrow frequency bands. This type of oscillator is essentially a primary standard and is not suitable for employment in portable or semifixed equipment. It appears that further study may advantageously be applied to cavity-controlled oscillators of types somewhat similar to those described above. The characteristics of these basic types can be further improved by means of several expedients. The first and most obvious method is to construct cavities which truly exhibit a zero coefficient of expansion. Further refined applications of Stupalith or pure Invar may closely realize this objective. A second method is to improve the effective Q of the cavity by employing it as a lightly loaded four-terminal device in the feedback loop of an otherwise frequency-insensitive vacuum-tube amplifier circuit. This arrangement would include the high-Q temperature insensitive cavity as the primary frequency-controlling device but might also include two other cavities as plate and cathode loads for the

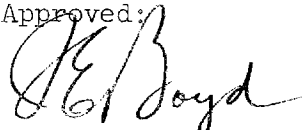
vacuum tube. These latter cavities would, by one of various known methods, be made to retain a relatively high Q but to present a very slow rate of change of reactance versus frequency.

Other methods of improving upon the performance of the present oscillators might be cited. A suggested method of improvement of Q of the re-entrant type oscillator is to eliminate the large circulating currents at the shorted ends of the plate and the cathode lines by closing these ends upon themselves, thus forming a closed ring and producing a doubly re-entrant form of oscillator. Finally, the direct cavity control may be supplemented by an AFC system employing the crystal discriminator which has been shown to perform satisfactorily at frequencies above 500 mc.

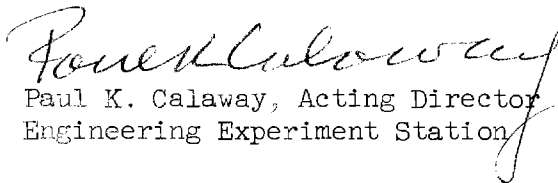
A quite different form of precision control involves a synchronization process in which the periodically interrupted stable frequency is injected as a locking signal into a free-running oscillator. It has been demonstrated at lower frequencies that the oscillator may be synchronized by any one of the significant frequencies in the spectrum of the interrupted source, hence a multifrequency form of control may be realized by this principle.

In final summary, it appears that considerable work remains to be done in simplifying and improving oscillators which can be made available for any desired section of the UHF band of frequencies. Further improvement in cavities is needed, particularly at higher frequencies where the coaxial cavity is no longer practicable and efforts should be directed toward reducing the temperature sensitivity of cavities suitable for these higher ranges.

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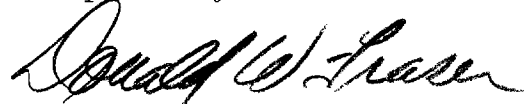


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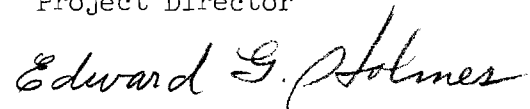


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